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DEVELOPMENT OF A FREQUENCY-DOMAIN
ELECTROMAGNETIC SCATTERING
MEASUREMENT SYSTEM

by

Kenneth K. Oh

December 1993

Thesis Advisor: Michael A. Morgan

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Development of a Frequency-Domain Electromagnetic Scattering Measurement System

by

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ABSTRACT

This thesis describes the development of a system for measuring frequency-domain scattered fields in the Transient Electromagnetic Scattering Range at the Naval Postgraduate School. The new system employs a stepped-frequency CW waveform and utilizes an HP-8510B network analyzer as an RF front-end and a coherent receiver. A pair of AEL H1498 antennas was installed to cover a frequency range of 2 GHz to 18 GHz. An HP-82300C BASIC Language Processor was installed on a COMPAQ Deskpro-386 PC, and an HP-BASIC program was developed for remote control of the HP-8510B with data acquisition over the HPIB bus. A post-processing algorithm was created using MatLab for background subtraction, calibration, and deconvolution. A set of RCS measurements was made using various size spheres, and the post-processing outputs were compared to computed values. Good agreement between these measurements and computed data indicates excellent accuracy of the measurement system and valid operations of the post-processing algorithm.

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I. INTRODUCTION

A. BACKGROUND

A radar detects targets at far distances by transmitting radio waves and listening for echoes resulting from fields scattered by the target. The scattered fields vary significantly with the radar frequency and polarization and with the target's shape, materials, and orientation. Knowledge of the scattering properties of potential targets is essential in designing and assessing performance of radar systems. On the other hand, scattering aspects of new military vehicle designs must be considered to enhance their survivability against enemy radars and weapons. Because radars play increasingly important roles in modern warfare, research to develop efficient and accurate techniques of measuring scattering properties of radar targets has become a high-priority task.

Given a knowledge of the incident wavefield, the electromagnetic properties of a radar target are completely described by the scattered wavefield. The strength of the scattered field is indicated by the target's radar cross section (RCS), a parameter widely used in the radar community. Although the RCS is a normalized scalar measure of the complex scattered wavefield, the term is often used to

describe the scattering characteristics of a target. Scattering responses of the target can be measured either in the time or frequency domain and the two responses are related by a Fourier transform.

The Transient Electromagnetic Scattering Laboratory (TESL) at the Naval Postgraduate School (NPS) currently utilizes a time domain technique to measure scattered fields. The system transmits short pulses and measures the target scattering response directly using a sampling oscilloscope. Time-domain techniques are considered faster, less expensive, and better suited to direct observations of transient scattering responses than frequency-domain techniques. However, frequency-domain techniques are considered more stable, less susceptible to noise, and capable of spanning a wider measurement frequency range.

B. OBJECTIVE

The objective in this thesis research is to develop a capability for measuring frequency-domain scattered fields over the 2 to 18 GHz range. The effort consists of installing and integrating an HP-8510B network analyzer system, mounting antennas on a wall panel in an anechoic chamber, installing an HPIB controller in a personal computer, writing an HP BASIC program for remote system control and data acquisition, creating a MatLab signal processing algorithm for background subtraction, calibration

and transformation to the time domain, and conducting RCS measurements on simple targets for validation. The new frequency-domain system will complement the existing time-domain RCS measurement system and should yield similar results when frequency-domain data are transformed into the time domain. Measurement validations for complex targets will be possible through comparing time and frequency-domain results acquired independently.

The thesis is divided into six chapters. Chapter II illustrates the system and measurement setup. Detailed descriptions are given for the anechoic chamber, the HP-8510B network analyzer, and the antennas. Chapter III explains the system control and data acquisition including controller hardware, data acquisition software, and measurement procedures. Chapter IV describes signal processing software for background subtraction and calibration. Fast Fourier Transform (FFT) techniques to recover time transient responses from frequency domain data are discussed, in addition to important processing aspects of windows, conjugation, and zero padding. Chapter V addresses system validation by presenting results of measurements on different size spheres. Finally, conclusions and future considerations are presented in Chapter VI.

II. SYSTEM DESCRIPTION AND MEASUREMENT SETUP

A. OVERVIEW

The frequency-domain scattered field measurement system, depicted in Figure 1, is implemented on an HP-8510B network analyzer [Ref. 1] using its stepped frequency mode. The system consists of an HP-8340B synthesized sweeper as an RF source, an HP-8511A frequency converter as an RF front end, an HP-8510B network analyzer as an IF receiver, AEL H1498 multi-octave horns serving as transmitting and receiving antennas, and an IBM PC-compatible computer with HP-82300C BASIC Language Processor as a data acquisition workstation and remote system controller.

System components are selected for scattered field measurements of 2 to 18 GHz. The system operates by spanning the frequency band with 801 steps. The maximum number of frequency steps allowed by the analyzer is used to maximize the unambiguous time extent.

For each frequency step, the system is phase-locked and continuous-wave (CW) signals are transmitted through the transmitting antenna in an anechoic chamber. The RF energy reflected by the target is collected by the receiving antenna, and initially down-converted to 20 MHz using a harmonic mixer in the frequency converter, followed by a

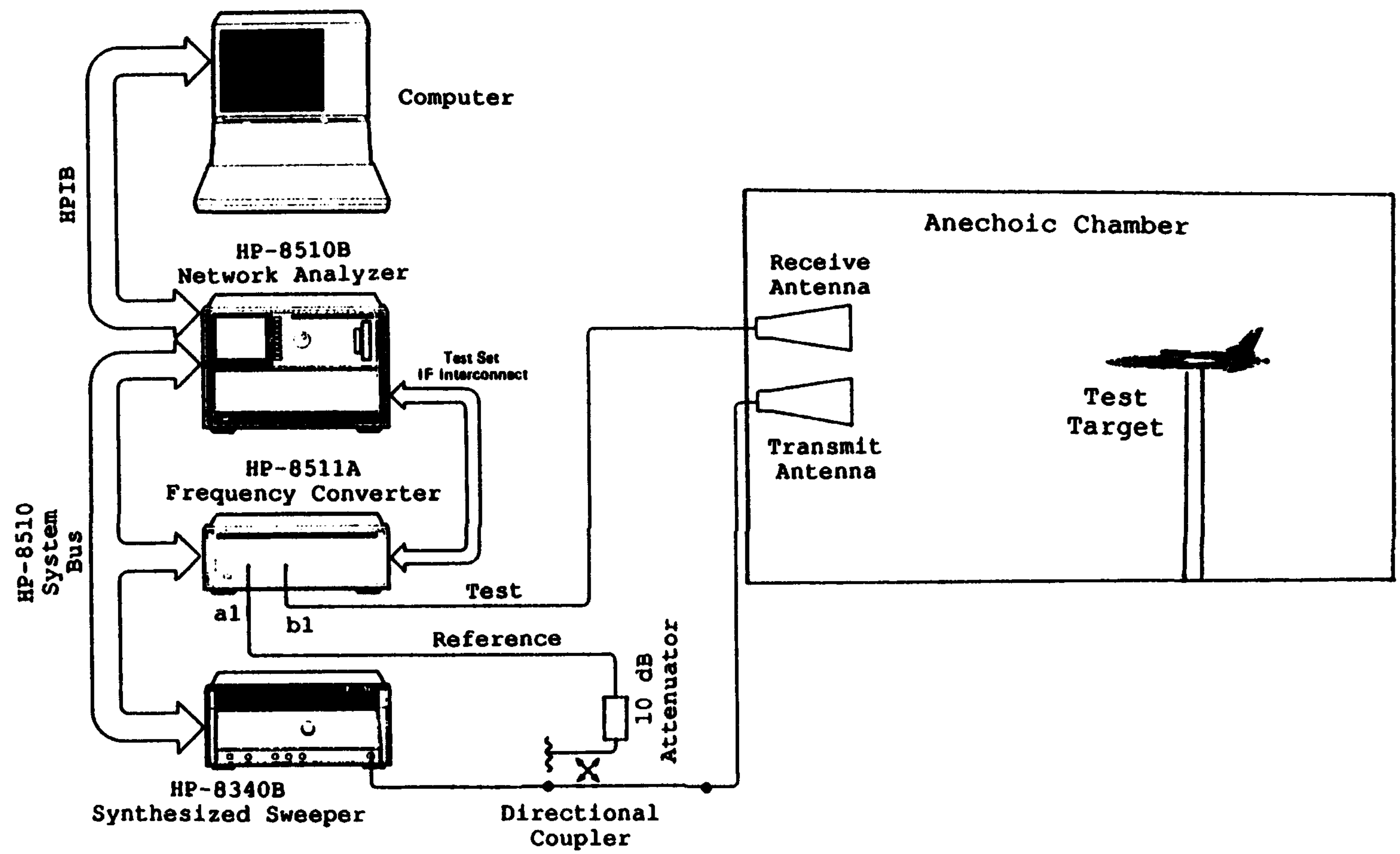

Figure 1. Schematic Drawing of the Frequency Domain Scattered Field Measurement System Implemented on the HP-8510 Network Analyzer. [Ref. 1]

second mixer which produces an IF frequency of 100 KHz for subsequent analcg-to-digital (A/D) conversion. This IF signal is processed through the "b1" channel in the frequency converter. For coherent detection with phase information, a constant RF signal is coupled using a 22 dB directional coupler at the RF source and down-converted through the "a1" channel. Amplitude and phase information for the specific frequency are established by comparing the "b1" channel (signal channel) to the "a1" channel (reference channel). The HP-8510B periodically sends a command to the synthesizer to change to the next frequency step until all 801 frequencies are measured.

The magnitude and phase data for 801 frequencies are transferred from the HP-8510B to the computer over the HPIB bus, stored on the internal hard disk, and subsequently processed with a digital signal processing algorithm written in MatLab.

B. SYSTEM DESCRIPTION

1. Anechoic Chamber

The anechoic chamber, shown in Figure 2, is located in room 535 of Spanagal Hall, measures 3.1 x 3.1 x 6.2 meter in height, width, and length and is shielded using aluminum sheet metal. Antennas mounted on the source wall illuminate targets supported on a low-density styrofoam column positioned 2.3 meters away. The source wall is covered with

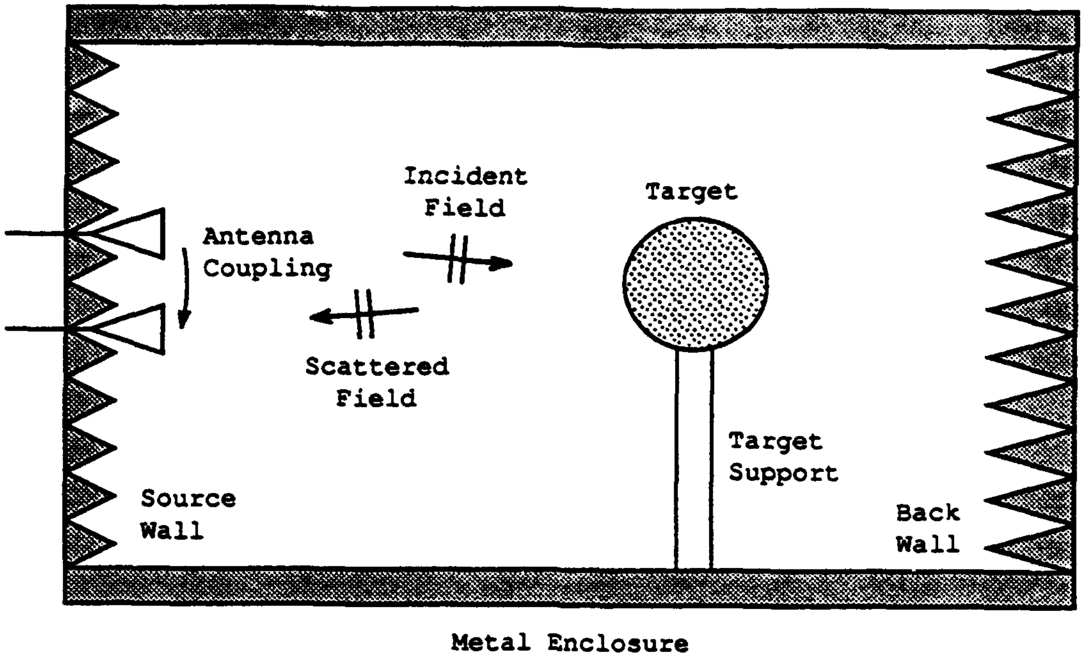

Figure 2. General Layout of the Anechoic Chamber

21 cm pyramidal radar absorbing material (RAM) and the back wall is covered with 46 cm pyramidal RAM. Sidewalls, floor, and ceiling are covered with longitudinal wedge RAM to direct energy towards the absorbing back wall. Figure 3 shows the chamber interior looking from the back wall. Further details of the chamber can be found in References 2 and 3.

2. HP-8510B Network Analyzer

The HP-8510B network analyzer, shown in Figure 4, is a high-performance measurement instrument designed to make microwave measurements of many kinds. In the course of this thesis effort, the HP-8510B network analyzer was configured as a phase-locked scattered field measurement system that

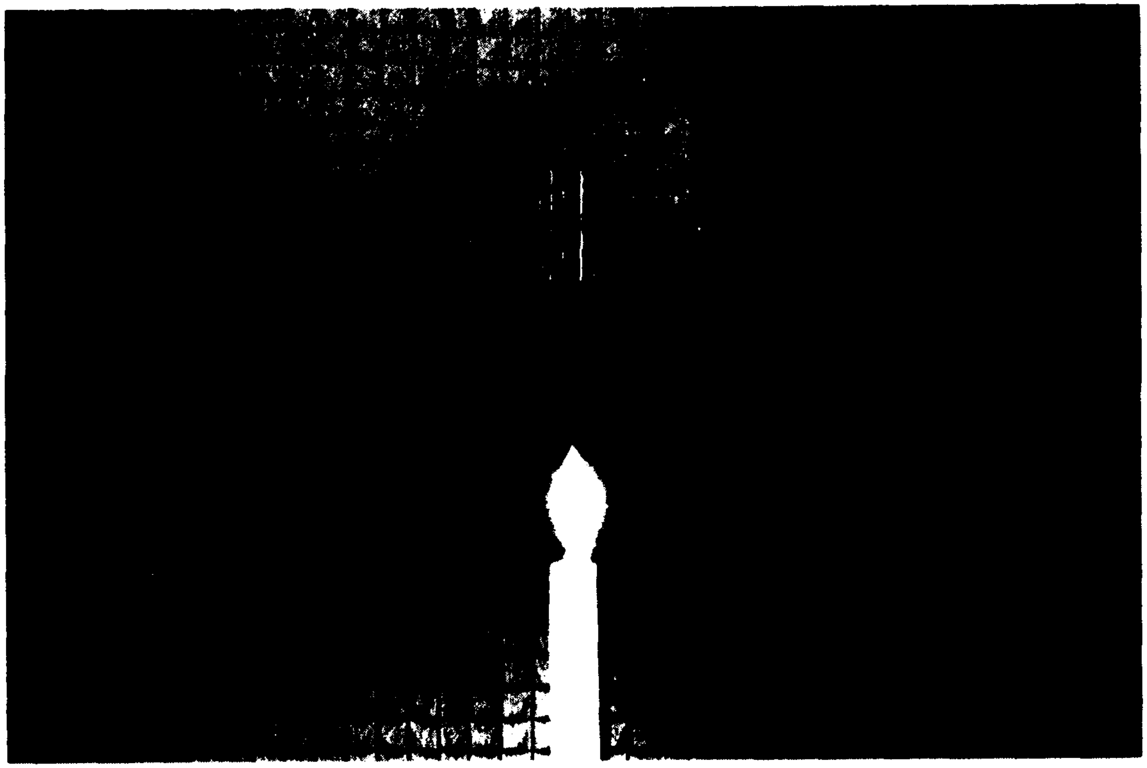

Figure 3. Interior of the Anechoic Chamber

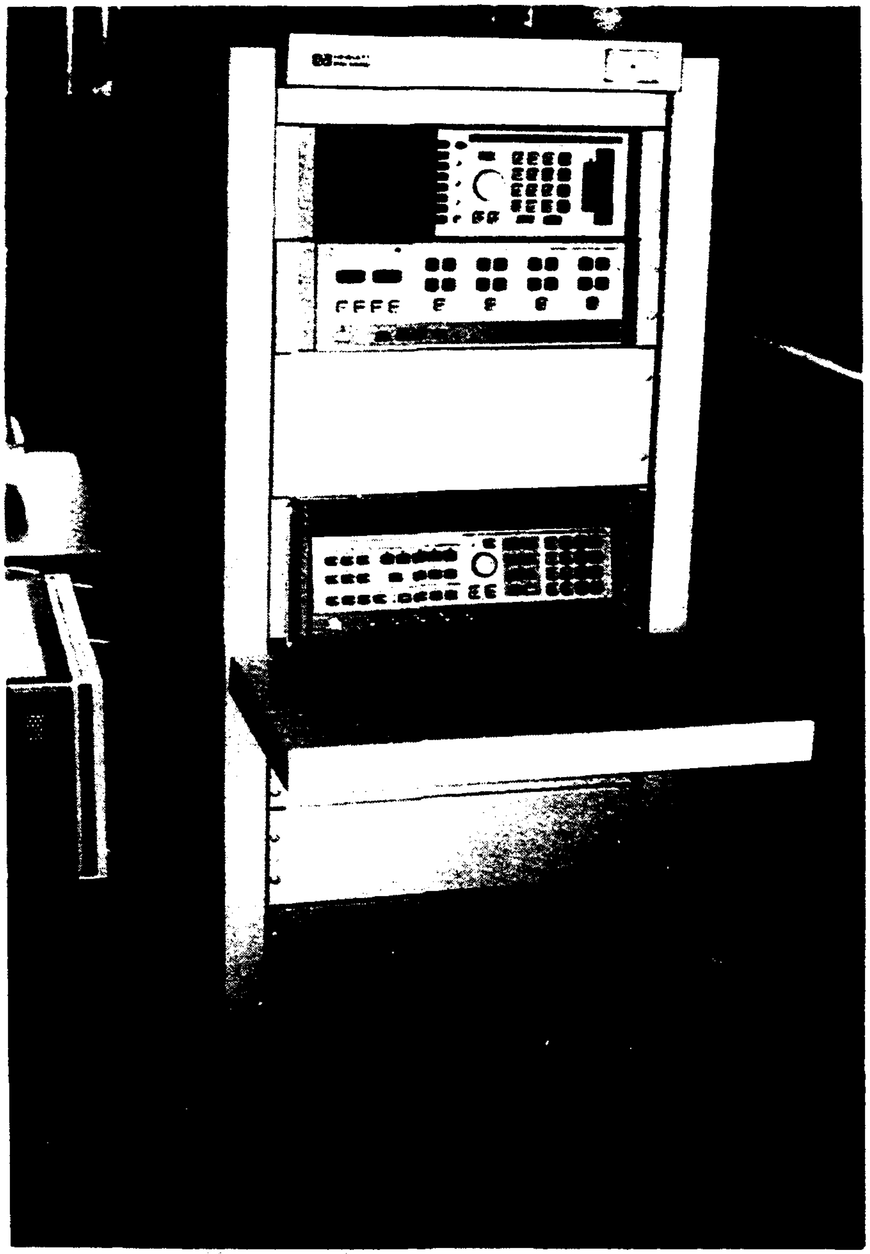

Figure 4. HP-8510 System Mounted on a Rack

offers very broad frequency coverage, wide dynamic range, and high measurement sensitivity. The HP-8510B network analyzer system consists of a microwave source (HP-8340B), RF front end (HP-8511A), and the HP 8510B as IF receiver and system controller. The HP-8510B controls the RF source and test set over a dedicated HP-8510B system bus. The HP-8511A RF front end provides a broad bandwidth of 45 MHz to 26.5 GHz and wide dynamic range of 75 to 105 dB, depending on averaging factor. The HP-8511A uses a harmonic sampling technique to convert the RF signals at its two inputs to 20 MHz IF signals that are subsequently processed by the HP-8510B.

In manual operation, the front panel keys of the HP-8510B are used to define measurement parameters and control the measurement process. In remote operation, the personal computer controls the HP-8510B by sending commands over the HPIB bus to execute the measurement process.

To measure amplitude and phase, the HP-8510B must have a reference signal that remains constant during the measurement. The phase-locked reference signal is obtained using an HP-11691D 20 dB, 2-18 GHz directional coupler inserted between the HP8340B RF source and the transmitting antenna. The measured amplitude and phase data are transferred to the personal computer over an HPIB bus.

For wideband scattered field measurements, the HP-8510B network analyzer can operate either in RAMP mode or in STEP mode. In RAMP mode, the source is swept in a continuous

analog sweep from the lower to upper frequency and the data is sampled without stopping the sweep. In STEP mode, the source is tuned and phase-locked to each of the 801 frequency sample points. The STEP mode is more stable in terms of frequency accuracy and source power level than the RAMP mode. The STEP mode will be used in all results of this thesis.

3. Antennas

AEL H1498 multi-octave horns [Ref. 4] are used for transmit and receive antennas to meet wideband requirements. This coaxially-fed, double-ridged horn antenna covers the 2-18 GHz frequency band. Average electrical characteristics are listed in Table 1 and performance over the 2-18 GHz frequency range is shown in Figure 5.

TABLE 1. ELECTRICAL CHARACTERISTICS OF AEL H1498 ANTENNA

Frequency (GHz)	VSWR	Avg. Gain (dBi)	Avg. 3dB Beamwidth E Plane	Avg. 3dB Beamwidth H Plane	Max. Power (Watts)
2 - 18	2.5:1	11	50°	45°	50

The antennas are mounted on a 24-inch square wood panel covered with aluminum sheet which is tightly fitted into a square opening in the source wall. The panel is covered with the same radar absorbing material as the source wall to eliminate multi-path effects between the antennas and the panel. The antennas are displaced vertically with the E-plane in the horizontal direction to minimize coupling. They are shimmed to point the beam at the target to minimize

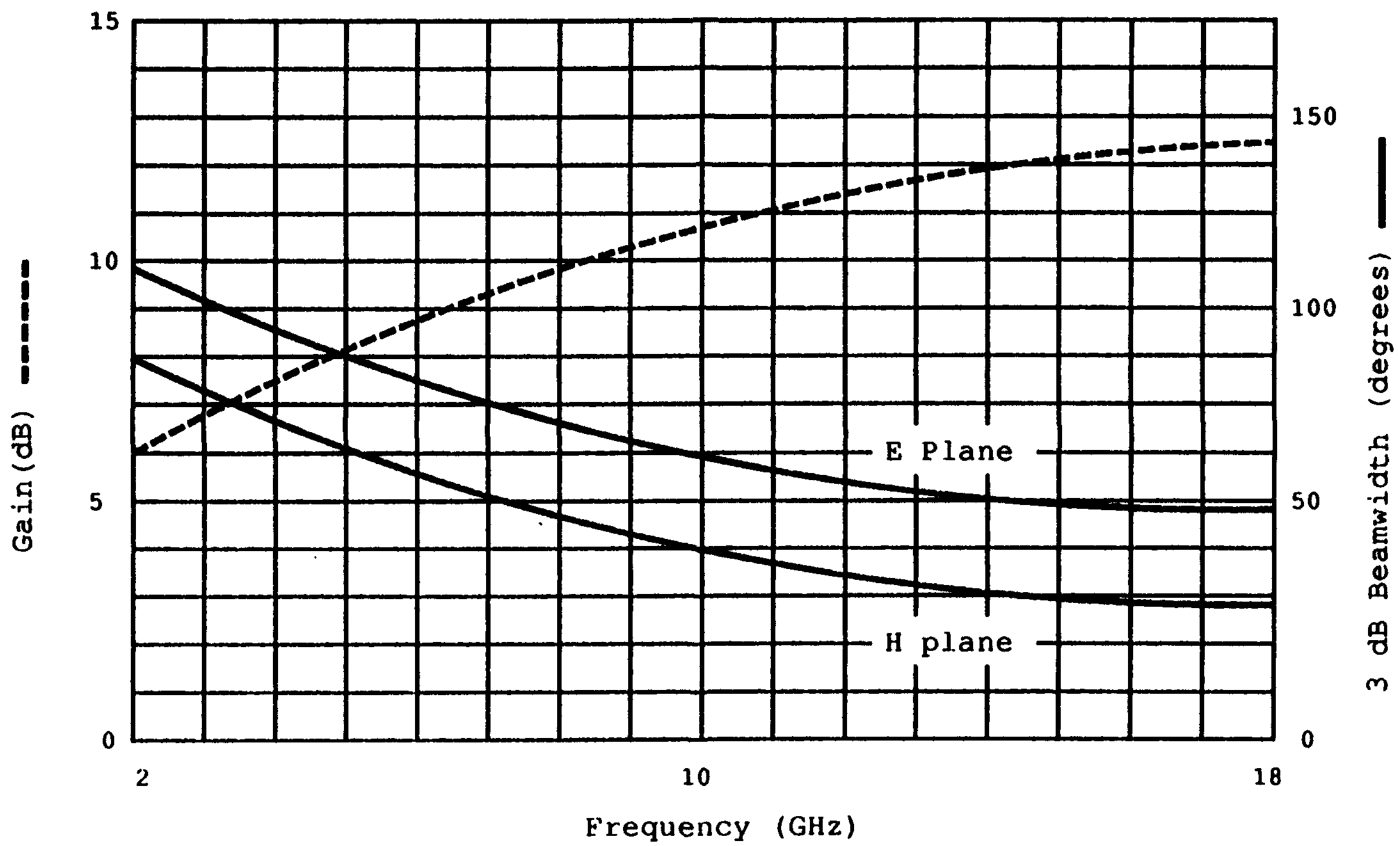

Figure 5. Performance Curves for the AEL H1498 Antenna. [Ref. 4]

boresight errors. Figure 6 shows the panel covered with RAM material.

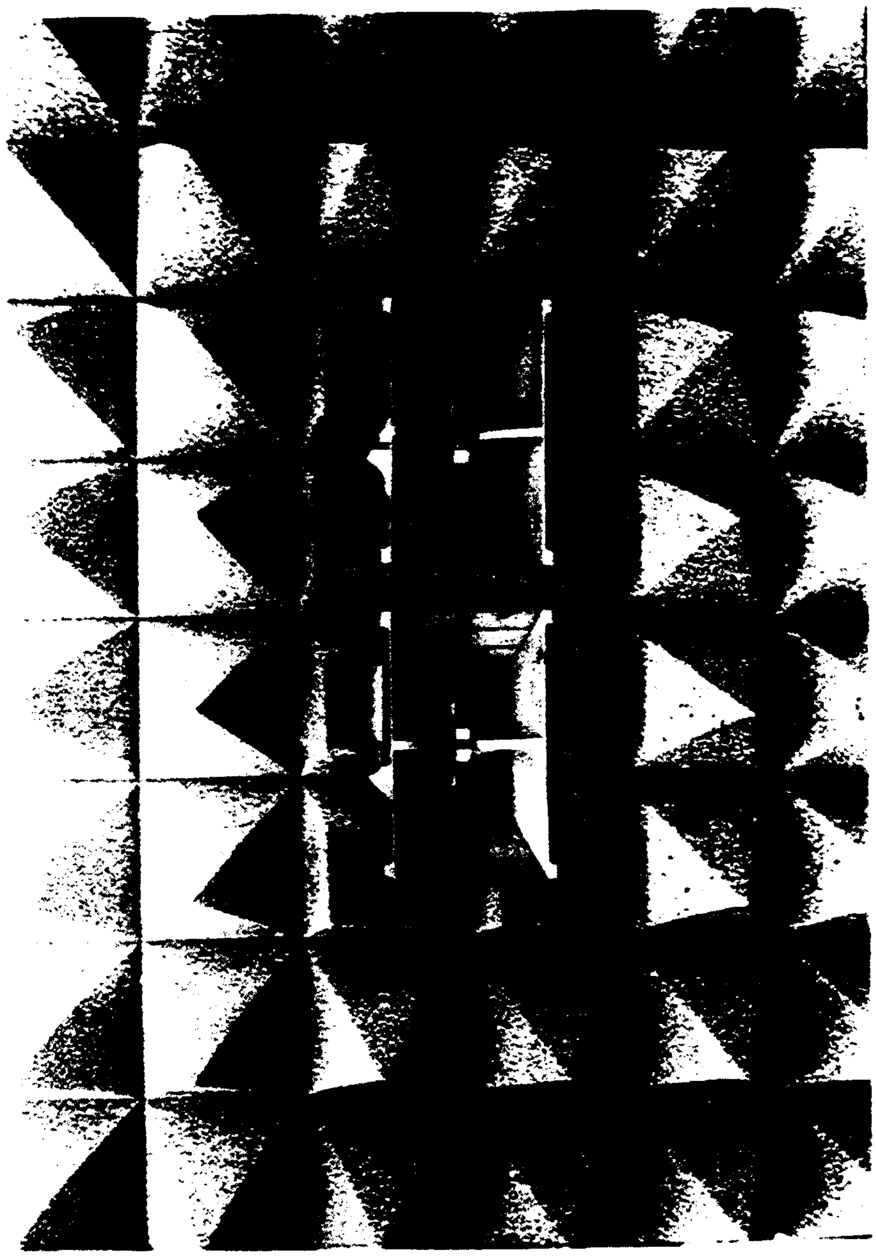

Figure 6. Masking of Panel with Radar Absorbing Material

III. REMOTE CONTROL AND DATA ACQUISITION

A. REMOTE CONTROLLER HARDWARE

The HP-8510B is used to define measurement parameters and control the measurement process; it can be operated manually with front panel keys or remotely through an HPIB bus. In remote operation, measurement parameters such as frequency range, number of frequency points, and averaging factor, can be set from a computer by sending proper commands on the HPIB bus. A COMPAQ Deskpro-386 computer using an HP-82300C BASIC Language Processor [Ref. 5] with a built-in HPIB interface was chosen as a remote system controller.

The HP-82300C BASIC Language Processor consists of an MC68000 processor card, HP-BASIC interpreter, emulator software, 4 megabytes of RAM memory, and a built-in HPIB interface. The processor card fits into a standard 16 bit ISA slot of the computer. The HP-BASIC interpreter and emulator software provide the capabilities of an HP-300 BASIC workstation while retaining all the capabilities of MS-DOS. Bi-directional communication between HP-BASIC and DOS applications allows data acquired by BASIC to be stored in DOS ASCII format on the PC hard disk.

B. CONTROL AND DATA ACQUISITION SOFTWARE

Control and data acquisition software, named "GET_DATA", is written in HP-BASIC and runs on the HP-82300C BASIC Language Processor within the PC. The software controls the HP-8510B, acquires measured data through the HPIB bus, and writes this to the PC hard disk.

After the PC is booted up, the user types "cd blp" to change to the blp directory. The name "blp" stands for basic language processor, and is a default name given when the BASIC Language Processor is installed. The user then types "basic" to cause the HP-BASIC interpreter to run on the PC. From this point, the PC runs as an HP-300 BASIC workstation, and the user issues HP-BASIC commands until quitting HP-BASIC by typing "[control]-F10" and returning to the DOS environment.

When HP-BASIC runs, the user types "LOAD "GET_DATA"". This BASIC command loads the program from the hard disk to RAM. When the user types "RUN", the program executes and takes over control of the HP-8510B. The preceding executions are summarized as follows:

```
c:\> cd blp

c:\BLP> basic

LOAD "GET_DATA"

RUN
```

When the "GET_DATA" program runs, the computer CRT displays the main-menu function keys at the bottom and the current HP-8510B status parameters such as start frequency, stop frequency, number of frequency points, RF source power level, sweep mode, active calibration set, and averaging factor at the top. The user can recall a default setup and start measurements by pressing appropriate function keys.

The main-menu function keys are shown in Figure 7, and their function is described below.

Continu.	Single	Hold	Change	Record	Playback	Change	Default
Sweep	Sweep	Sweep	#Average	Data	Data	Setup	Setup

Figure 7. Main-menu Function Keys

Continu. Sweep - Pressing this function key causes the HP-8510B to sweep continuously through the 801 frequency points, to transmit RF energy and update data.

Single Sweep - Pressing this function key causes the HP-8510B to start sweeping from the first frequency point to the last frequency point. When the single sweep is completed, the RF transmission is shut off and the data are stored in the HP-8510B until the "Continu. Sweep" key or "Single Sweep" key is pressed for new data.

Hold Sweep - Pressing this function key halts the frequency sweeping and shuts off RF transmission.

Change #Average - Pressing this function key alters the averaging used to increase signal-to-noise ratio. In STEP mode, averaging is done at each frequency as the HP-8510B steps through the 801 frequency points. The averaging factor can range from 1 to 4096. The measurement time increases proportionally as the averaging factor increases. The data in the results section were measured with the averaging factor of 128.

Record Data - Pressing this function key causes the writing of two data files. The first file begins with a letter "D" and is in a DOS ASCII format, the second file begins with a letter "F" and is in an HP-BASIC binary format. The contents of these two files are exactly the same. Each line of 801 rows lists a frequency index, magnitude in dB, and phase in degrees. After two plots are drawn on computer CRT, the program is paused until a "continue" function key is pressed to resume.

Playback Data - Pressing this function key allows a user to retrieve old data and display them on a computer CRT. The program reads the HP-BASIC binary format file.

Change Setup - Pressing this function key allows the user to change measurement parameters on the HP-8510B remotely.

Default Setup	- Pressing this function key sets measurement

parameters to default values. The default values are 2-18 GHz, 801 frequency points, STEP mode, continuous sweep, a source power of 10 dBm, and an averaging factor of 16.

When the "Change Setup" function key is pressed, a setup sub-menu will be displayed. The function keys for the setup sub-menu are shown in Figure 8.

Save State	Recall State	Change Freq	No. of Point	Power Level	Sweep Mode	Calibra-tion	Go to Mainmenu

Figure 8. Setup Sub-menu Function Keys

Save State - Pressing this function key saves a complete HP-8510B state into a storage register in the HP-8510B. All measurement parameters are included in the saved state.

Recall State - Pressing this function key recalls a saved state.

Change Freq - Pressing this function key allows the user to change frequency range.

No. of Point - Pressing this function key allows the user to set the number of frequency points to 51, 101, 201, 401 or 801.

Power Level - Pressing this function key allows the user to set the power level of the RF source.

Sweep Mode - Pressing this function key allows the user to

select either STEP mode or RAMP mode.

Calibra-
tion - Pressing this function key activates the HP-8510B internal error correction feature.

Go to
Mainmenu - Pressing this function key causes the main menu to be displayed.

The program can be stopped by pressing "[shift]-pause". The source code may be edited by typing "EDIT". The program must be stopped before "EDIT" is executed. Further details of the HP-BASIC programming can be found in Reference 1, and the "GET_DATA" source code can be found in Appendix A.

C. MEASUREMENT PROCEDURES

The first step is to power up the HP-8510B system and boot up the computer and allow a 30-minute warm-up for the synthesizer. Next, load the "GET_DATA" program. When the program runs, press the "Default Setup" function key to set the HP-8510B to a default setup. Use the "Change Setup" key to change the setup. For the data in this thesis, the default setup is first recalled, and then the averaging factor is changed to 128.

When the setup is completed, press "Hold Sweep" key to halt RF radiation. This step may be skipped if the user believes the RF radiation level is not a health hazard.

All measurements require three steps: calibration, background, and target scattering. In the first step, place a metallic sphere calibration target on the target column. Press "Single Sweep" key. Sweeping through all 801 points takes 40 seconds to 200 seconds depending on the averaging factor. When sweeping is done, press "Record Data" key. When two plots are displayed, press "Continue" key and type in a number such as 123 for filenames of "D123.DAT" and "F123.DAT". The input statement is programmed to accept only numeric inputs and not alphanumerics. If the user desires other names, the DOS "rename" command can be used in the DOS environment after the data acquisition program is terminated. Remove the calibration target, and measure the background by pressing the "Single Sweep" key. Press the "Record Data", and assign a new number to the background data. Then, place the target on the column and repeat the single sweeping and recording for the target data.

Three data files have been saved on the PC hard disk: calibration, background, and target. These files will be subsequently processed by the MatLab program. If more target measurements are required, the preceding three steps can be repeated for a new target, using new names for the stored files.

IV. POST-PROCESSING

A. ALGORITHM OVERVIEW

The RCS of a target is a function of frequency, polarization, and target orientation and should be independent of measurement instrumentation and anechoic chamber conditions. However, the raw data obtained from RCS measurements contains unwanted effects such as noise, antenna coupling, chamber clutter, antenna gain, and distance to target.

The unwanted effects fall into two groups; the first is caused by extraneous signals such as noise, antenna coupling and chamber clutter, and the second is caused by the dependence of the measurement system on transmitting power level, cable loss, antenna gain, distance to target, and receiver mixer performance. In an ideal case, the receiver output in the absence of the target should be zero. Due to residual scattering of chamber RAM and significant coupling between the transmitting and receiving antennas, however, an undesirable background signal exists in all measured data. This undesirable signal can be removed by measuring the background data and performing a complex subtraction from the target data. The dependence on the measurement system can be removed by measuring a calibration sphere of known scattering

characteristics and the target of interest and forming the ratio of the measured responses multiplied by the computed field response of the calibration sphere.

Once the frequency domain scattered fields of the target are established by the background subtraction and calibration process, transient time responses are obtained through an inverse Fourier transform. For a time transient response using efficient inverse FFT, complex conjugates and zeros are appended to the frequency-domain data, as will be shown. Finally, time-gating the transient response around the target and Fourier transformation back to the frequency domain smoothes out the frequency data and provides refined RCS levels.

B. BACKGROUND SUBTRACTION AND CALIBRATION

Operation of the measurement system is represented by the signal flow diagram in Figure 9. The RF excitation is

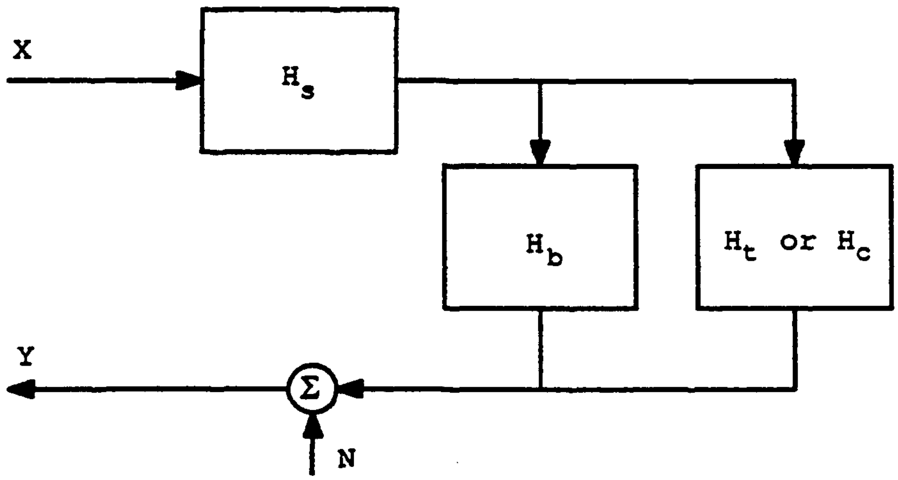

Figure 9. System Signal Flow Diagram

denoted by X, and the signal out of the network analyzer by Y. The symbol, H_s, represents the transfer function of combined measurement system dependence which includes RF cable loss, both antenna characteristics, two-way free-space loss from antennas to target, and RF mixer conversion loss. The symbol, H_t, is the frequency response of the target, and H_c is that of the calibration sphere. Both H_t and H_c are the ratios of the scattered field at the location of the receiving antenna to the incident field at the location of the scatterer, multiplied by the one-way free-space spread factor, as defined in Equations (1) and (2).

$$H_t = R\ (4\pi)^{1/2}\ \frac{E^s \text{ (at the receiving antenna)}}{E^i \text{ (at the target)}} \tag{1}$$

$$H_c = R\ (4\pi)^{1/2}\ \frac{E^s \text{ (at the receiving antenna)}}{E^i \text{ (at the calibration sphere)}} \tag{2}$$

where H_t = frequency response of target
H_c = frequency response of calibration sphere
E^s = scattered electric field
E^i = incident electric field
R = distance from the receiving antenna to the target

Background errors such as antenna coupling and chamber clutter are grouped together and denoted by H_b. The chamber thermal noise and receiver mixer noise are denoted by N.

Equations (3)-(5) can be written from the signal relationship.

$$Y_t = X\ H_s\ (H_t + H_b) + N_t \tag{3}$$

$$Y_b = X\ H_s\ (\ 0 + H_b) + N_b \tag{4}$$

$$Y_c = X\ H_s\ (H_c + H_b) + N_c \tag{5}$$

where Y_t = signal out of network analyzer in target measurement

Y_b = signal out of network analyzer in background measurement

Y_c = signal out of network analyzer in calibration sphere measurement

X = RF excitation

H_s = frequency response of measurement system dependency

H_b = frequency response of background

An estimator of the frequency response of the target, H_{te}, can be derived by a simple algebraic manipulation of Equations (3)-(5). This will be termed the calibration process.

$$H_{te} = H_{cc}\ (Y_t - Y_b)\ /\ (Y_c - Y_b) \tag{6}$$

The estimator becomes exact as the measurement noise approaches zero.

As shown in Equaton (6), the target frequency response can be calculated from the three measured data and the computed frequency response of the calibration sphere, H_{cc}. The measurement system dependency, H_s, cancels out in

deriving Equation (6). From the definition in Equation (1), the radar cross section, σ, is given by

$$\sigma = |H_t|^2 \tag{7}$$

Raw data taken from the network analyzer, Y_t, is shown in Figure 10. The antenna coupling is substantially larger than the target scattering at the lower frequencies so that the background signal dominates over the target signal. Figure 11 shows the target scattering after the background is subtracted out; the antenna coupling and chamber clutter are eliminated. The measurement system dependency is removed in the calibration process of Equation (6), and the result is shown in Figure 12. The spikes in the data are caused by a residual antenna coupling and chamber clutter, and will be greatly reduced by time-domain gating to be discussed in the following section.

C. DIGITAL SIGNAL PROCESSING

1. Window Shape

The frequency-domain data are weighted with a window function prior to inverse FFT in order to reduce sidelobes in the time domain. Among many window shapes available in the MatLab signal processing library, the Hamming window [Ref. 6], which is a raised cosine function, was determined to be best suited because the effects of windowing can be removed by multiplying the data with an inverse of the window

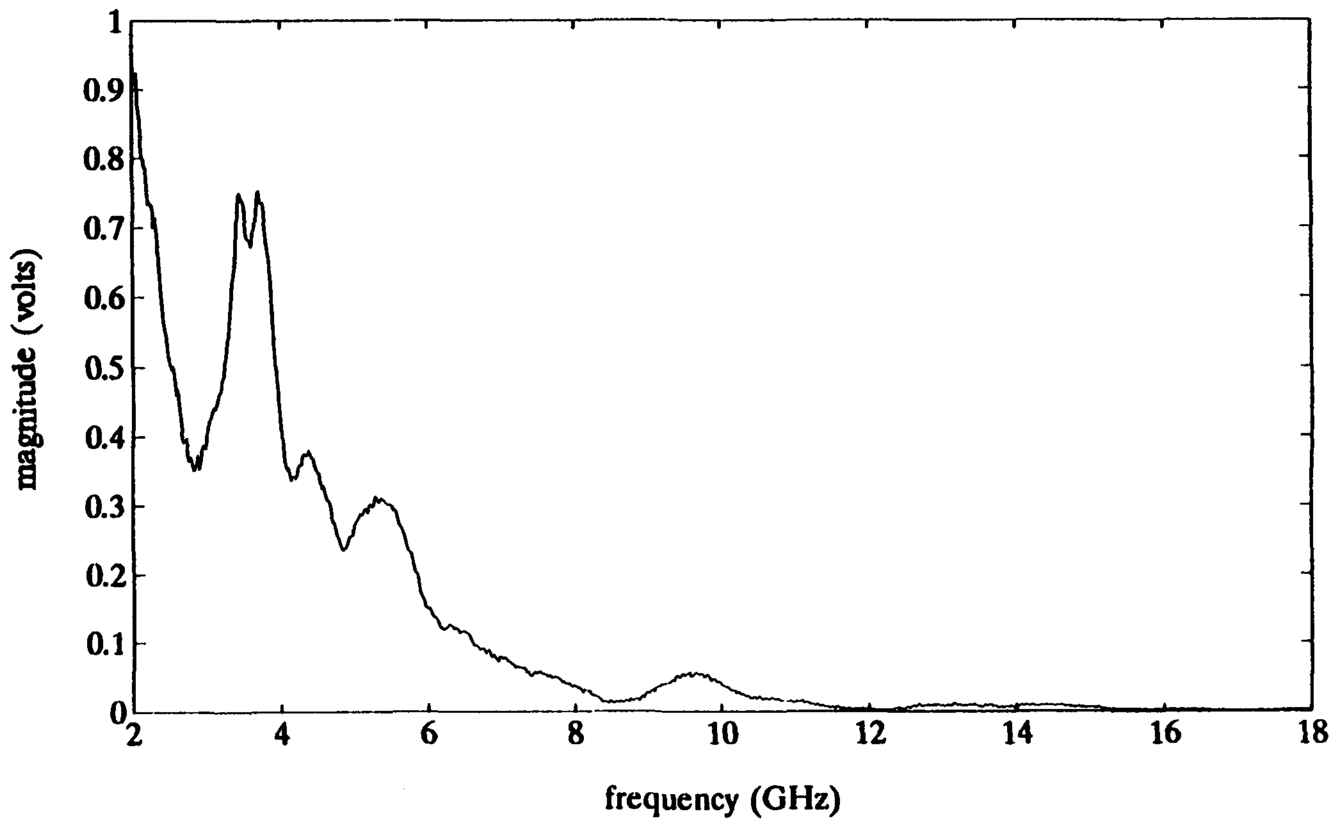

Figure 10. Target Raw Data

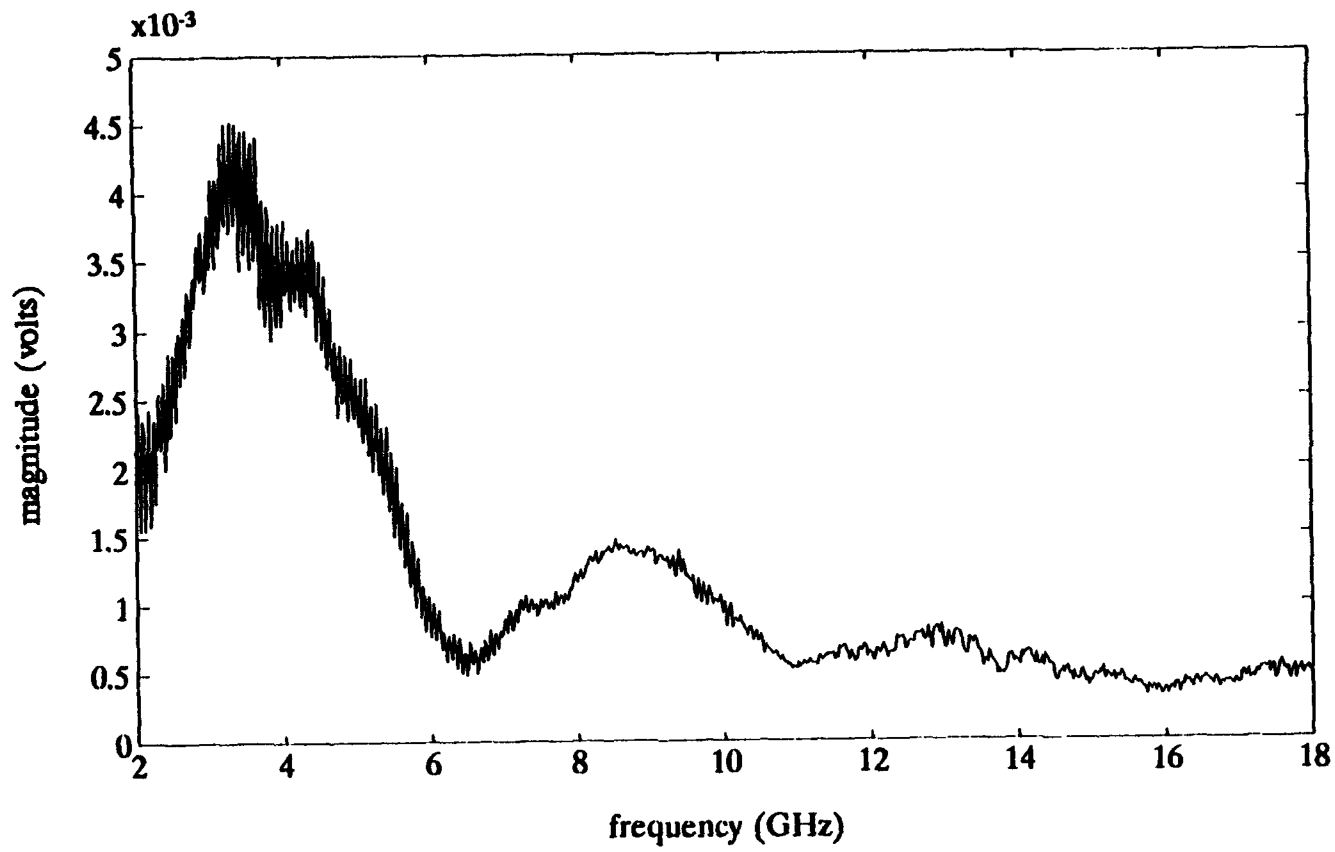

Figure 11. Frequency Response after Background Subtraction

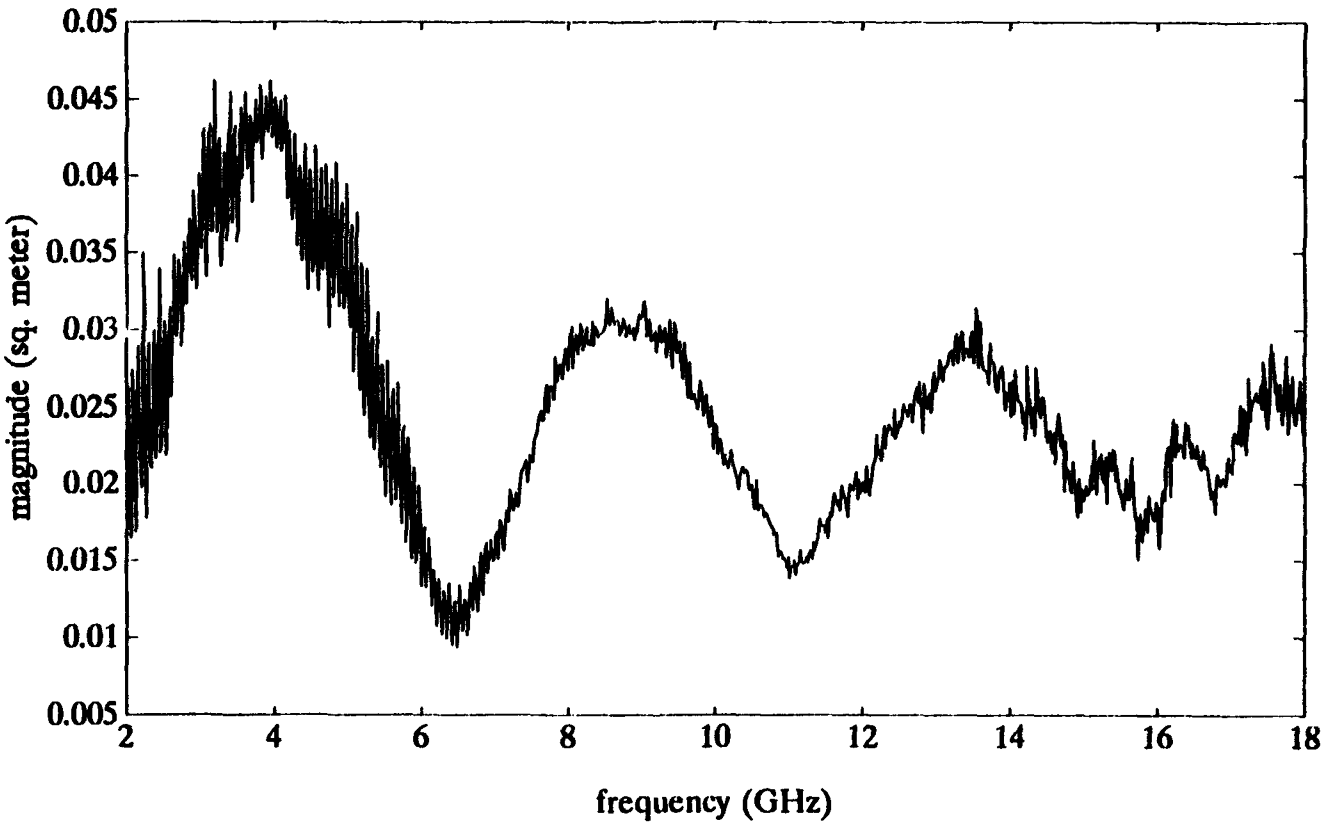

Figure 12. Frequency Response after Calibration

function. Other windows have zero end values so that the inverse can not be taken. The actual equation of the Hamming window in the library is given in Equation (8).

$$W = 0.54 - 0.46*\cos(2*pi*n/(N-1)) \tag{8}$$

where W = weighting factor in the window function
N = total number of sample points
n = index ranging from 0 to N-1

The data in Figure 12 are Hamming-windowed and shown in Figure 13.

2. Zero-padding and Complex Conjugate

After the data are weighted with the Hamming window function, 100 data points with zero value are inserted in front of the windowed data to fill in the missing DC-2GHz data, and 123 zeros are appended to the end of the data to make the total number of data points 1024, thus allowing use of radix-2 FFT algorithm. The complex conjugates of the 1024 data points are added, making a total of 2048 data points. The complex conjugate is necessary to make the transformed time-domain data a time transient response. The layout of the 2048 data points is illustrated in Figure 14.

3. Fourier Transforms, Gating and Unwindowing

The 2048 data points in the frequency domain are transformed to the time domain with an IFFT routine in the MatLab library. The routine, IFFT(X), is the inverse discrete Fourier transform of vector X. The IFFT employs a

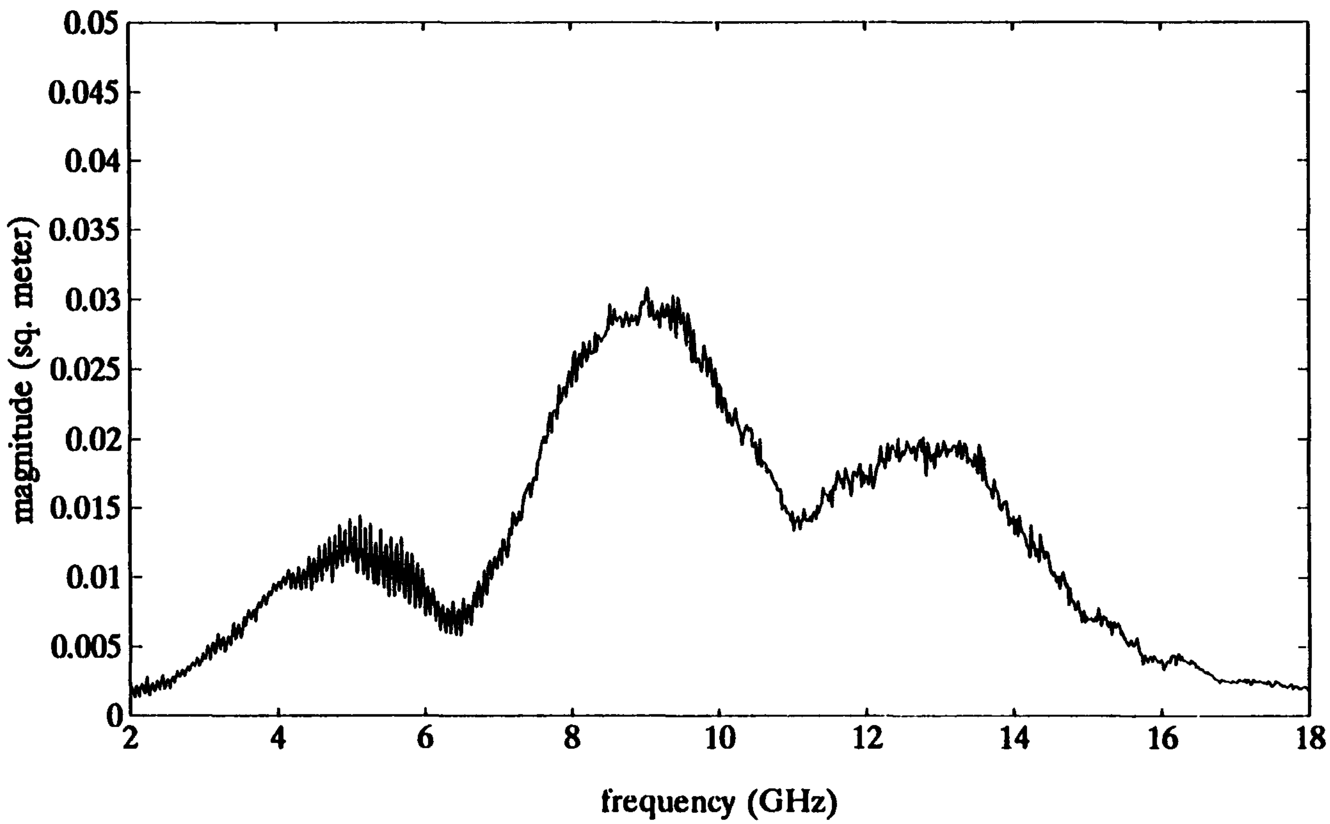

Figure 13. Frequency Response after Windowing

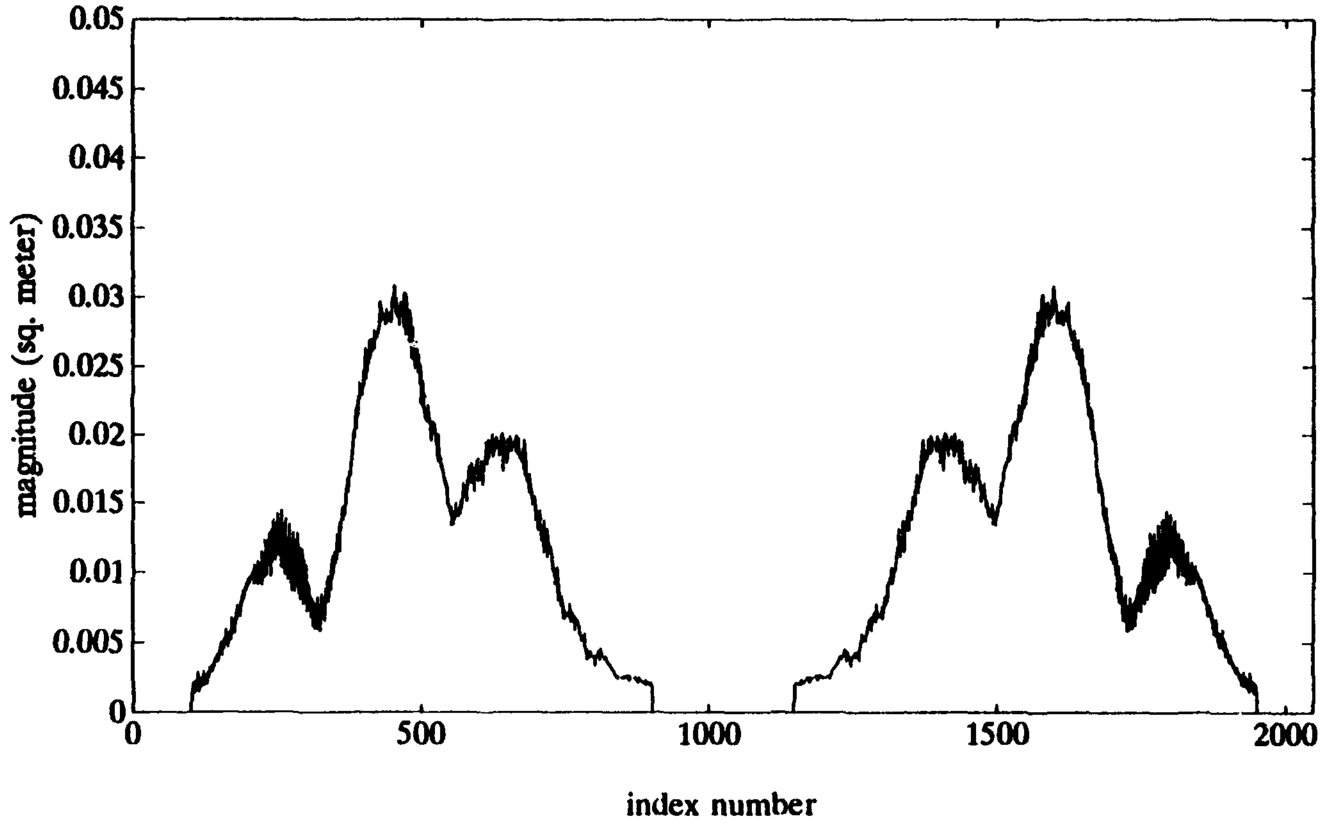

Figure 14. Frequency Response after Adding Zeros and Conjugates

fast radix-2 algorithm when the length of X is an integer power of two, and a slower algorithm when the length of X is not a power of two. The IFFT operation performed on the 2048 complex data points yields another set of 2048 complex numbers of which the imaginary part is zero, and the real part represents the time transient response.

In the time-domain plot, the position where the target appears depends on the phase reference in the computation of the calibration sphere. In order to place the antenna coupling at time zero and thus make the time transient response plot easier to read, the data are shifted 589 cells as shown in Figure 15. The wrap-around nature of the Fourier transform output permits the shifting of data without any loss or discontinuity. Shifting data in the time domain is equivalent to multiplication in the frequency domain by a linear phase term and does not affect the magnitudes.

After shifting, the time domain data are gated to remove residuals of antenna coupling and any return from the chamber which has not been eliminated completely in the background subtraction. The gate is centered at the 600th cell, and the width is 400 cells. The gate is centered on the target, and the gate width corresponds to approximately 10 nanoseconds.

The gated data are transformed back to the frequency domain with an FFT routine in the MatLab library. Because

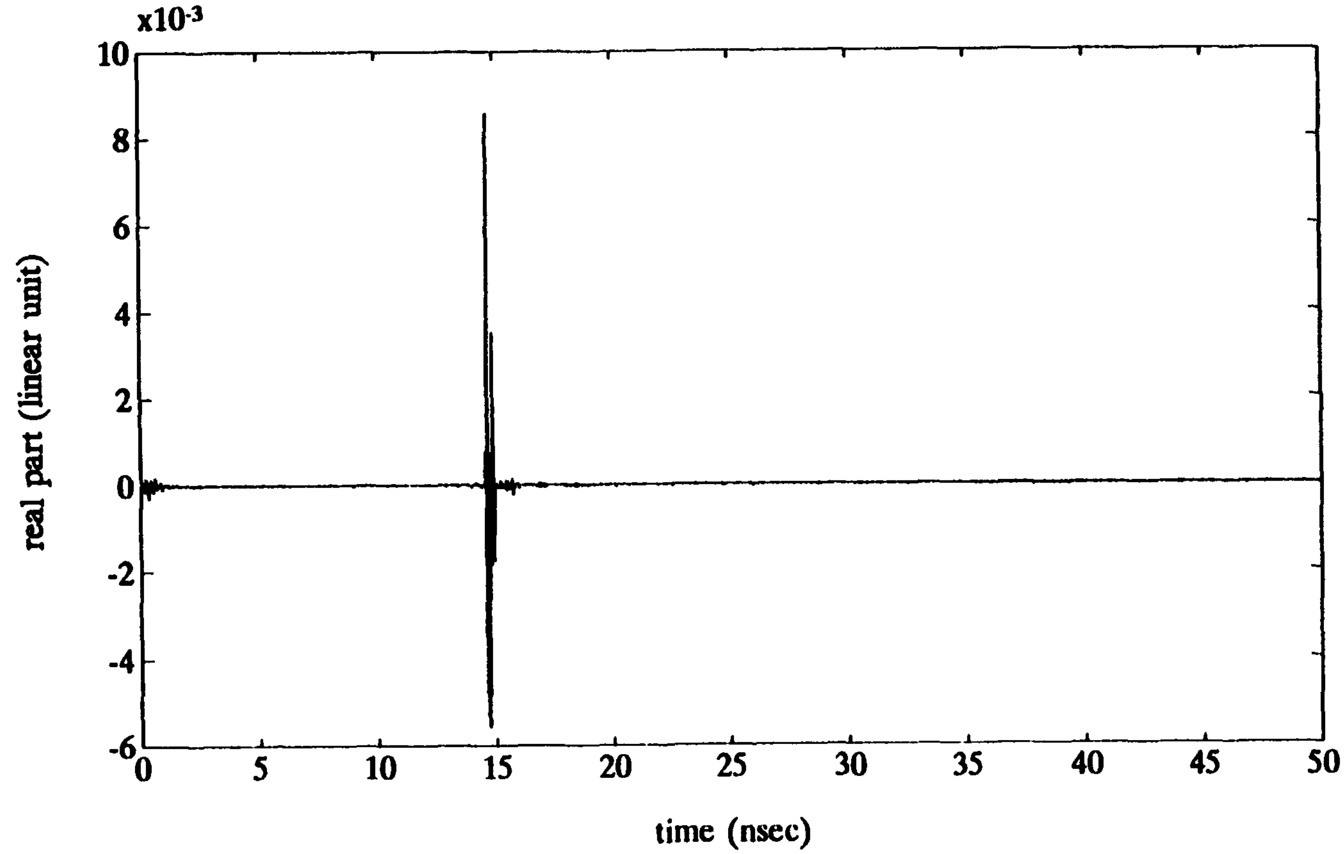

Figure 15. Time Response after Shifting

zeros and conjugates have been appended to the frequency data, the 801 data points between the 101st cell and the 901st cell represent the 2-18 GHz frequency range. Finally, an inverse of the Hamming window is applied to the 801 data points to remove the effect of windowing. The final data are shown in Figure 16 and the sharp spikes in Figure 12 are eliminated.

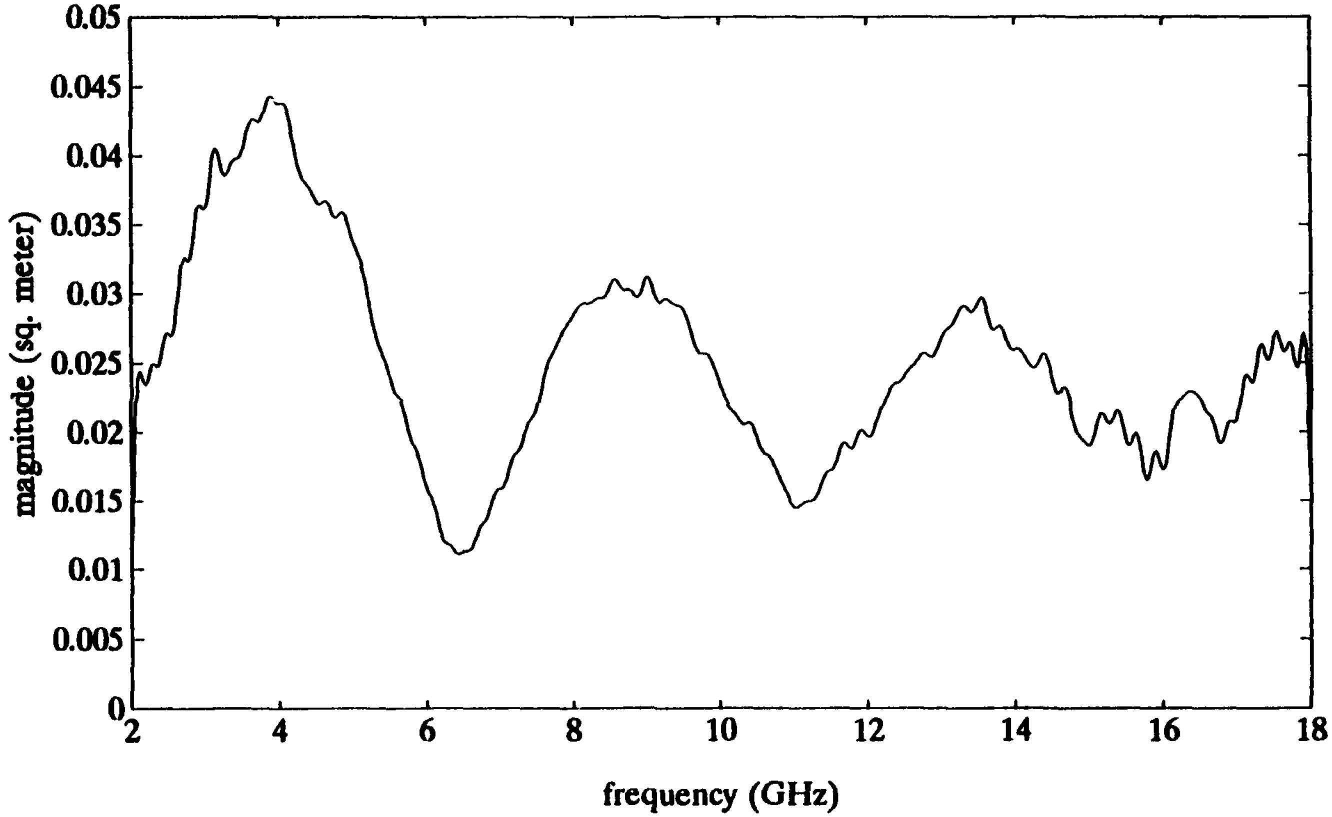

Figure 16. Frequency Response after Unwindowing

V. SYSTEM VALIDATION

A. CANONICAL TARGETS

A set of metal spheres was measured in the NPS TESL anechoic chamber in order to validate the fidelity of the frequency-domain scattering measurement system. Metal spheres were chosen as validation targets because: 1) the exact solution is readily available from the Mie series solution, 2) the RCS is aspect-independent so that errors in target positioning are negligible, and 3) the time transient response exhibits a delayed creeping wave which can be used to validate the time-domain transformation.

The computer *program*, *MIE.BAS* written by M. Morgan for the Mie series solution [Ref. 2], has been modified and named MIE2.BAS. Since the original MIE.BAS calculates the scattered field observed at the receiving antenna, the free-space spread factor defined in Equation (2) has been added to the new MIE2.BAS program. The output of MIE2.BAS is used in the post-processing program, PROC.M, for calibrating the measured data by supplying the H_{CC} in Equation (6).

B. EXPERIMENTAL RESULTS

A series of scattering measurements was performed on metal spheres in the frequency range of 2 to 18 GHz. The spheres were 15.24, 12.07, 7.94, and 2.54 centimeters(cm) in

diameter. Setup of the HP-8510B was in STEP mode sweep, 801 points, and averaging factor of 128. Antennas were oriented for horizontal polarization. The 12.07 cm sphere was arbitrarily chosen as a calibrator and the other spheres as targets. A test matrix is summarized in Table 2.

TABLE 2. TEST MATRIX OF SCATTERING MEASUREMENTS

Filename	Type	Descriptions
d101.dat	calibration	12.07 cm diameter sphere
d102.dat	background	empty chamber
d103.dat	target	2.54 cm diameter sphere
d104.dat	calibration	12.07 cm diameter sphere
d105.dat	background	empty chamber
d106.dat	target	7.94 cm diameter sphere
d107.dat	calibration	12.07 cm diameter sphere
d108.dat	background	empty chamber
d109.dat	target	15.24 cm diameter sphere

Three measurement steps were taken for each target: calibration, background, and target. With a 128 averaging factor, 60 seconds were required for a complete sweep of 801 frequency points, 15 seconds to transfer data from the HP-8510B to the PC, and 10 seconds to store this data to the hard disk. When no averaging is taken, sweeping through 801 frequency steps takes 40 seconds, most of it is for phase-locking the receiver. As the averaging factor increases, the

sweep time also increases progressively to the maximum of 700 seconds for the maximum averaging factor of 4096. Trade-offs between the averaging factor and the measurement time must be considered in selecting the averaging factor.

The MIE2.BAS program was executed for the 12.07 cm calibration sphere. The computation includes the small bistatic angle between two antennas and provides the magnitude and phase of H_{CC}. These data were stored under filenames of "mag.dat" and "faz.dat".

Results of the "PROC.M" post-processing program are shown in Figures 17 through 22. Figures 17, 19, and 21 show the frequency responses of the target spheres, with the measurement data plotted in dotted lines, and theoretical values from the Mie solution in solid lines. Comparison of the frequency responses shows good agreement, and thus confirms the validity of the measurement system. Figures 18, 20, and 21 show the corresponding time responses. The time responses represent the scattered waveform resulting from the incident impulse formed by the inverse transform of the 2-18 GHz bandlimited signal weighted by the Hamming window. The time responses show the main specular return, from the front face of the sphere, followed by the creeping-wave, delayed in time corresponding to a single circumnavigation.

A detailed comparison between the measurement data and computational data in the frequency responses indicates a minor discrepancy of less than 1 dB in magnitude. This

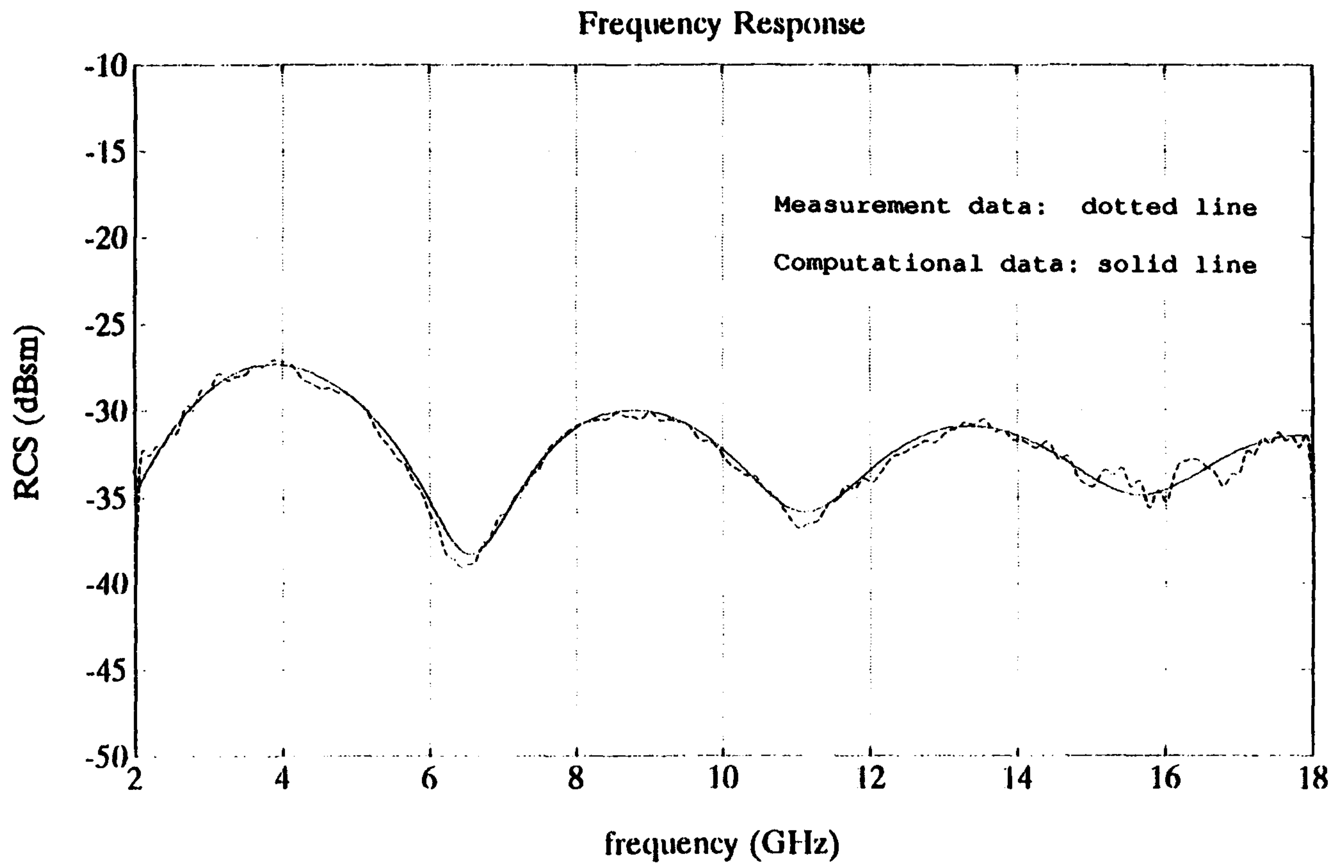

Figure 17. Frequency Response of a 2.54 cm Diameter Sphere

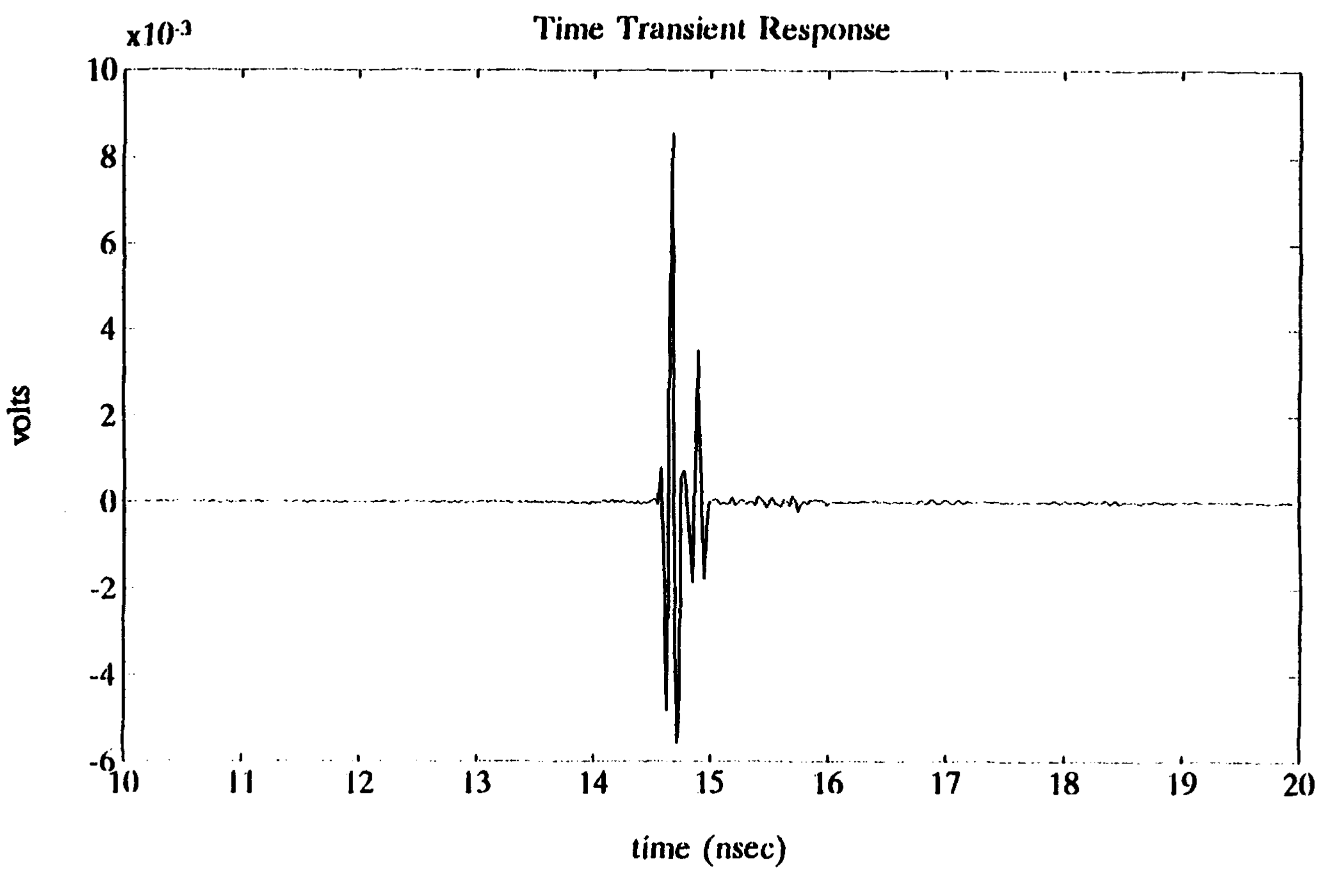

Figure 18. Time Transient Response of a 2.54 cm Diameter Sphere

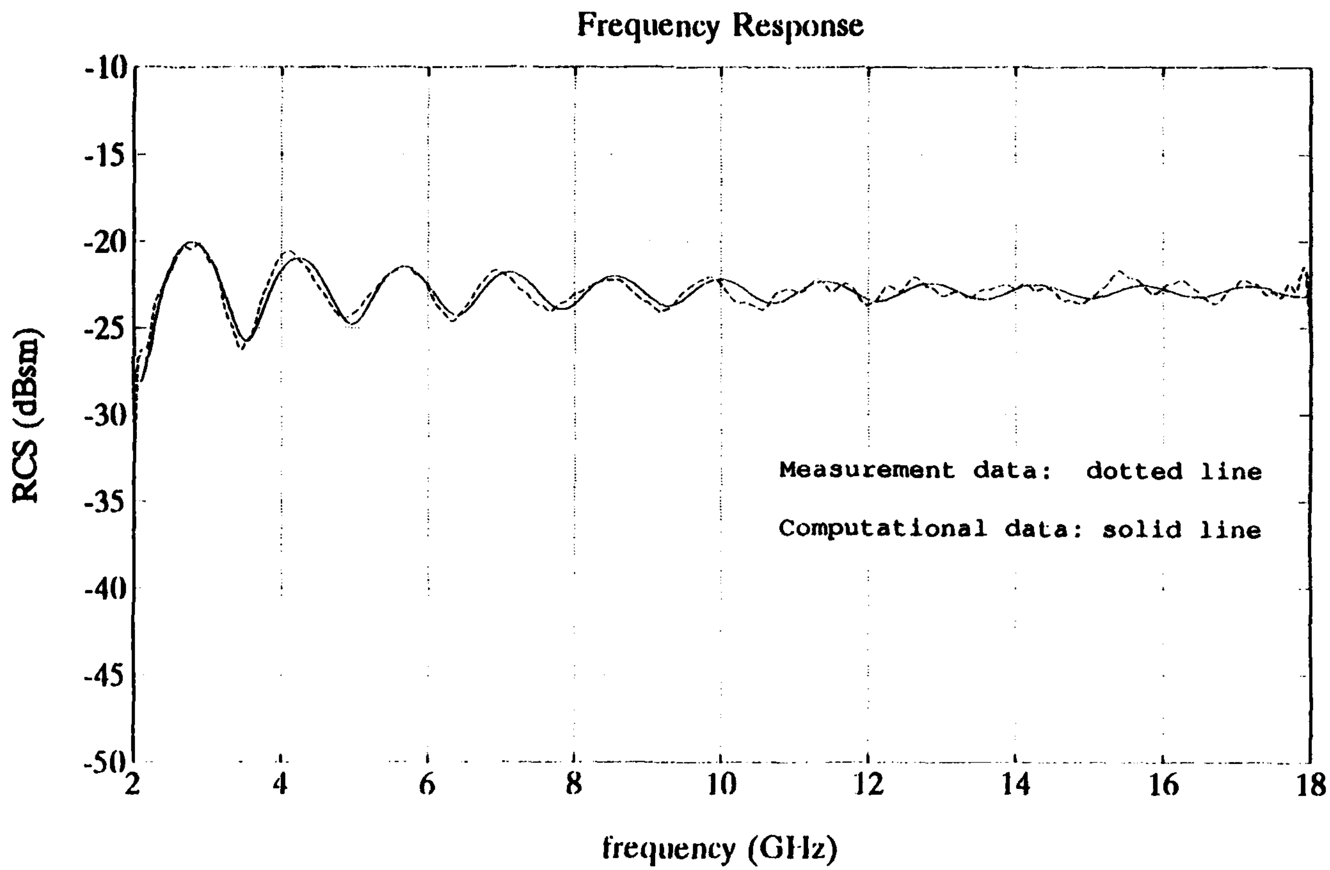

Figure 19. Frequency Response of a 7.94 cm Diameter Sphere

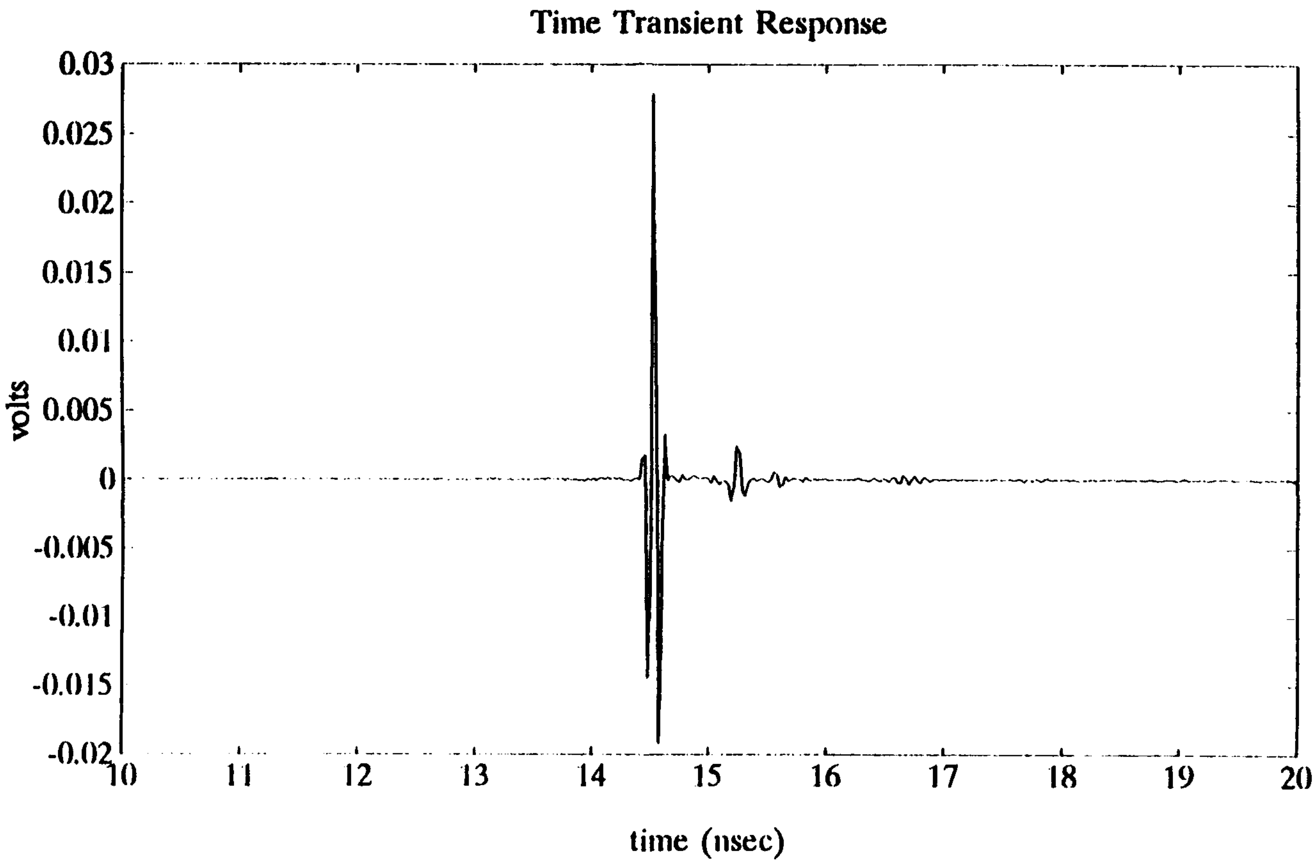

Figure 20. Time Transient Response of a 7.94 cm Diameter Sphere

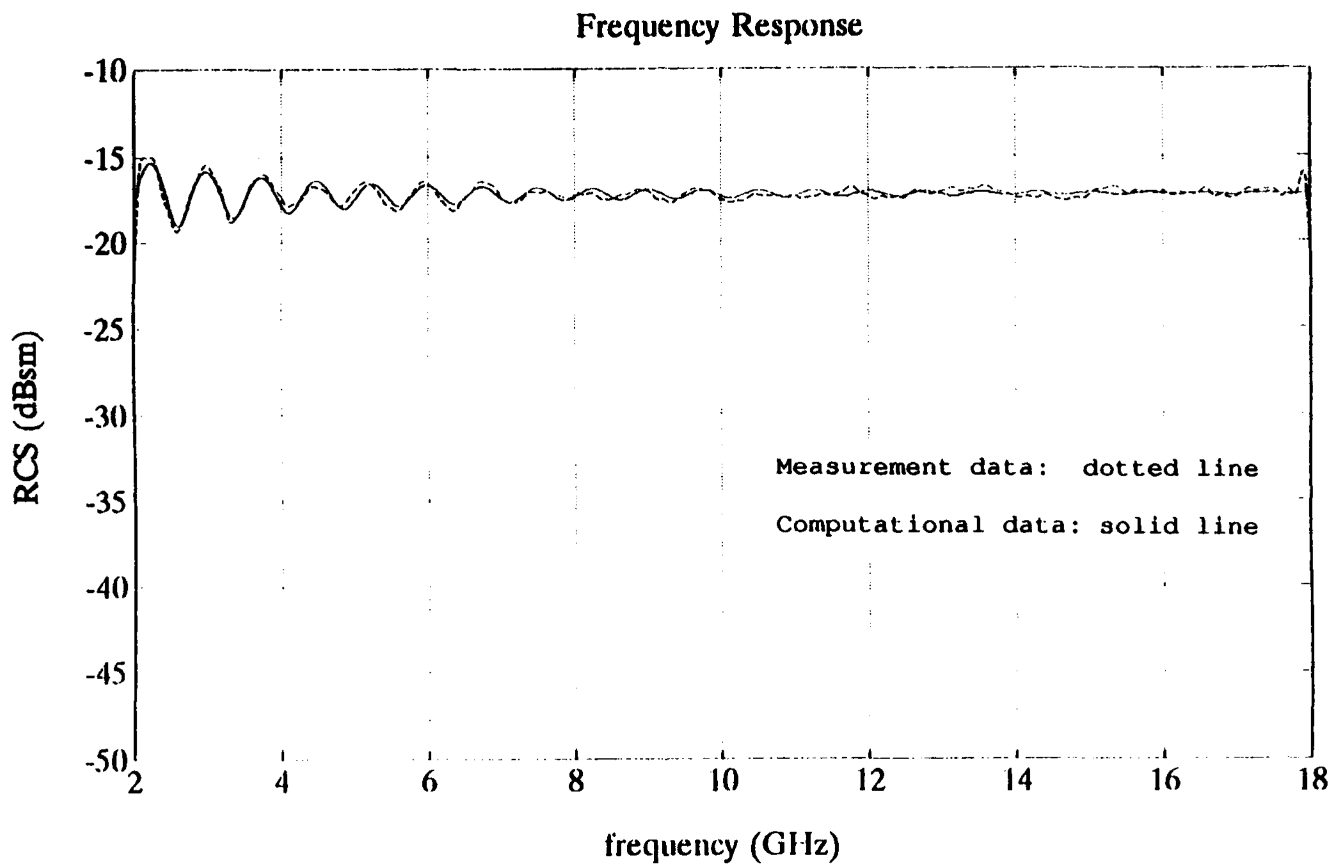

Figure 21. Frequency Response of a 15.24 cm Diameter Sphere

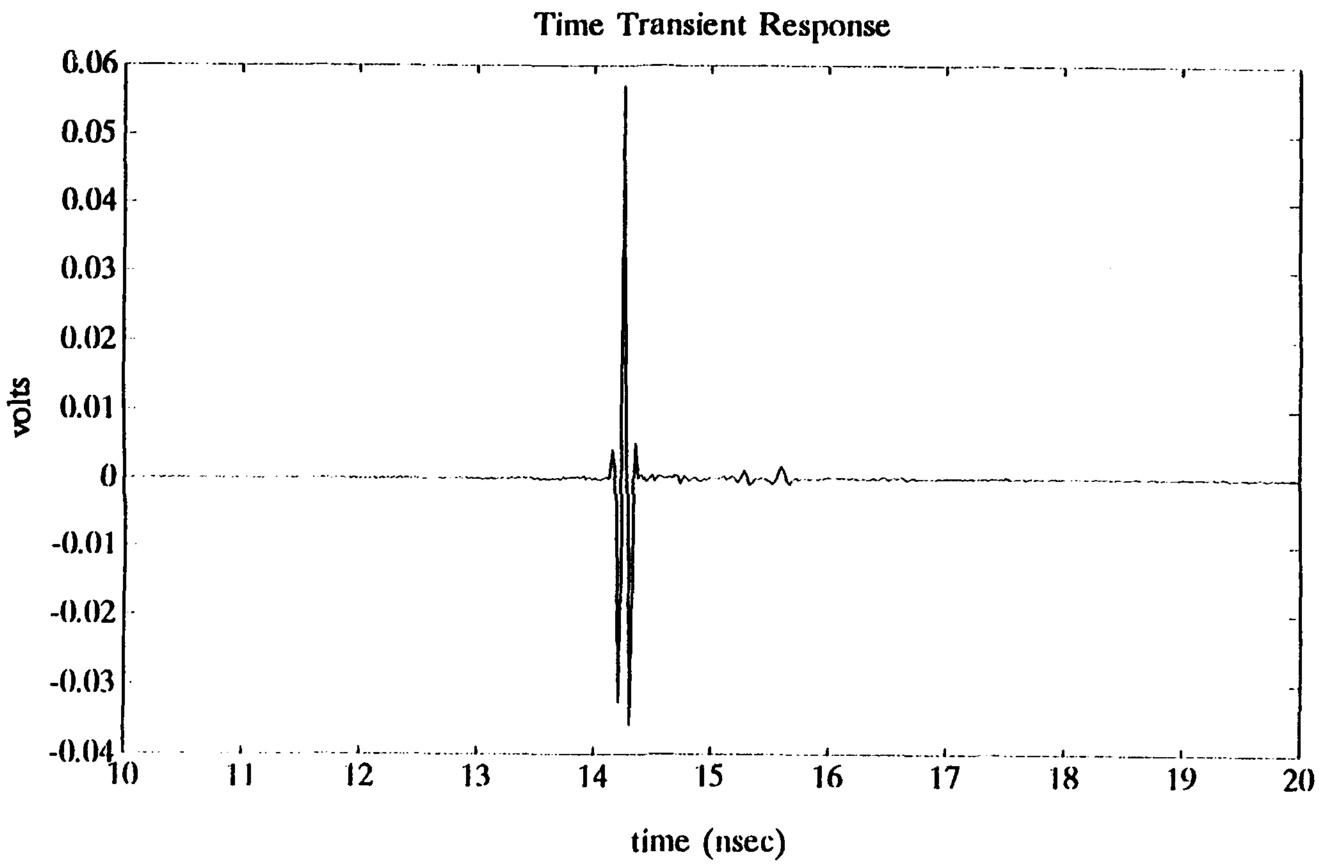

Figure 22. Time Transient Response of a 15.24 cm Diameter Sphere

discrepancy remained even when the averaging factor was increased substantially, showing that the error results from coherent sources. Possible error sources are 1) interaction between the sphere and the chamber, 2) disturbance of fields on the sphere caused by the target support column touching the sphere, 3) non-uniform field distribution in the target zone caused by the antenna beam pattern, and 4) imperfections in the sphere's surface radius, as well as scratches and dents. Despite these possible error sources, the measurement results are in good agreement with the computational data, thus confirming the validity of the measurement system and post-processing algorithm.

VI. CONCLUSIONS

A. SUMMARY

A new frequency-domain electromagnetic scattering measurement capability has been developed for the NPS TESL anechoic chamber. The new system takes advantage of the HP-8510B network analyzer for its broad frequency coverage, wide dynamic range, and automated control of sub-systems. A pair of AEL H1498 horns operating at 2 to 18 GHz is installed as transmitting and receiving antennas. An HP-82300C BASIC Language Processor installed on a COMPAQ Deskpro-386 PC enables remote control of the HP-8510B and data acquisition over the HPIB bus. A post-processing algorithm has been developed in MatLab for background subtraction, calibration, windowing, adding zeros and conjugates, IFFT, shifting, gating, and FFT.

The new system was utilized to measure the scattered fields from several different-size spheres. Good agreement between the measurements and computational Mie series demonstrated the validity of the measurement system and the post-processing algorithm.

B. FUTURE CONSIDERATIONS

The antenna component needs to be improved to enhance the measurement fidelity and expand the frequency bandwidth. For

low frequencies, the increased antenna coupling limits the dynamic range and SNR of the system. The coupling between antennas must be reduced by either moving them apart, inserting RAM between them, finding a new antenna that controls the coupling better, or gating the RF in hardware. The antenna also limits the frequency bandwidth. The frequency coverage of the current system can be increased to 26 GHz by upgrading the antennas and the directional coupler.

When the new improved antennas are implemented to reduce the antenna coupling, the RAMP mode of the HP8510B may be used to speed up the measurement time. In the RAMP mode, the network analyzer sweeps through the 801 frequency points in a fraction of a second.

One of the advantages of the HP-8510B based system is its flexibility for expansion into the millimeter-wave region. With a simple addition of a second RF source, frequency multipliers, and millimeter-wave components such as a directional coupler and antennas, the frequency range of the RCS measurement can be extended to 110 GHz.

One last consideration for the future is incorporating a pedestal for the rotation of targets. The ability to rotate the target in precise angle increments and correcting coherent data at different aspect angles allows the generation of two-dimensional scattering images of the target using inverse synthetic aperture radar (ISAR) techniques.

APPENDIX A. SOURCE CODE OF THE "GET_DATA" PROGRAM

```
10  ! GET_DATA:  THIS HP BASIC PROGRAM CONTROLS HP8510
20  !            REMOTELY AND WRITES MAG & PHASE DATA ON PC
30  !            HARD DISK UNDER C:\BLPSUBDIRECTORATE.
40  !            WRITTEN BY KEN OH
50  !            REVISED ON 9/2/93
60     OPTION BASE 1
70     COM REAL Exp_tbl(0:255)
80     MASS STORAGE IS "\BLP:DOS,C"
90     PRINTER IS 1
100    PRINT CHR$(12)
110    ASSIGN @Hpib TO 7
120    ASSIGN @Nwa TO 716
130    REMOTE @Hpib
140    CLEAR @Nwa
150    Exp_tbl(0)=2^(-15)
160    FOR I=0 TO 126
170      Exp_tbl(I+1)=Exp_tbl(I)+Exp_tbl(I)
180    NEXT I
190    Exp_tbl(128)=2^(-143)
200    FOR I=128 TO 254
210      Exp_tbl(I+1)=Exp_tbl(I)+Exp_tbl(I)
220    NEXT I
230 Main_menu: !
240    PRINT CHR$(12)
250    OUTPUT @Nwa;"STAR;OUTPACTI;"
260    ENTER @Nwa;Star_freq
270    OUTPUT @Nwa;"STOP;OUTPACTI;"
280    ENTER @Nwa;Stop_freq
290    OUTPUT @Nwa;"POIN;OUTPACTI;"
300    ENTER @Nwa;Npoint
310    OUTPUT @Nwa;"POWE;OUTPACTI;"
320    ENTER @Nwa;Power
330    OUTPUT @Nwa;"SWEM?;"
340    ENTER @Nwa;Swe$
350    OUTPUT @Nwa;"CALS?;"
360    ENTER @Nwa;Calset
370    OUTPUT @Nwa;"AVERON;OUTPACTI;"
380    ENTER @Nwa;Avn
390    OUTPUT @Nwa;"ENTO;"
400    DISP
410    PRINT "Main Menu"
420    PRINT " "
430    PRINT "START FREQ IS:";Star_freq/1.E+9;"GHz"
440    PRINT "STOP  FREQ IS:";Stop_freq/1.E+9;"GHz"
450    PRINT "NUMBER OF POINTS IS:";Npoint
```

```
460   PRINT "SOURCE POWER IS:";INT(Power+.001);"dBm"
470   PRINT "SWEEP MODE IS:";Swe$
480   PRINT "ACTIVE CAL SET IS:";Calset
490   PRINT "AVERAGING FACTOR IS:";Avn
500   OFF KEY
510   ON KEY 1 LABEL "Continu.Sweep" GOTO Cont_sweep
520   ON KEY 2 LABEL "Single  Sweep" GOTO Sing_sweep
530   ON KEY 3 LABEL "Hold    Sweep" GOTO Hold_sweep
540   ON KEY 4 LABEL "Change  #Average" GOTO Average
550   ON KEY 5 LABEL "Record  Data" GOTO Call_record
560   ON KEY 6 LABEL "PlaybackData" GOTO Call_playback
570   ON KEY 7 LABEL "Change  Setup" GOTO Setup
580   ON KEY 8 LABEL "Default Setup" GOTO Default
590   GOTO 510
600   !
610   !
620 Cont_sweep: !
630   DISP "CONTINUOUS SWEEP"
640   OUTPUT @Nwa;"CONT;"
650   GOTO Main_menu
660 Sing_sweep: !
670   DISP "SINGLE SWEEP  .... PLEASE WAIT"
680   OUTPUT @Nwa;"SING;"
690   GOTO Main_menu
700 Hold_sweep: !
710   DISP "HOLD SWEEP"
720   OUTPUT @Nwa;"HOLD;"
730   GOTO Main_menu
740 Average: !
750   INPUT "ENTER THE NUMBER OF AVERAGE:",Avn
760   OUTPUT @Nwa;"AVERON";Avn
770   GOTO Main_menu
780 Call_record:  !
790   DISP "RECORDING DATA.... PLEASE WAIT."
800   CALL Record_data(Npoint)
810   GOTO Main_menu
820 Call_playback:  !
830   DISP "READING DATA.... PLEASE WAIT."
840   CALL Playback_data(Npoint)
850   GOTO Main_menu
860 Setup: !
870   PRINT CHR$(12)
880   OUTPUT @Nwa;"STAR;OUTPACTI;"
890   ENTER @Nwa;Star_freq
900   OUTPUT @Nwa;"STOP;OUTPACTI;"
910   ENTER @Nwa;Stop_freq
920   OUTPUT @Nwa;"POIN;OUTPACTI;"
930   ENTER @Nwa;Npoint
940   OUTPUT @Nwa;"POWE;OUTPACTI;"
950   ENTER @Nwa;Power
960   OUTPUT @Nwa;"SWEM?;"
```

```
970    ENTER @Nwa;Swe$
980    OUTPUT @Nwa;"CALS?;"
990    ENTER @Nwa;Calset
1000   PRINT "Setup Menu"
1010   PRINT " "
1020   PRINT "START FREQ IS:";Star_freq/1.E+9;"GHz"
1030   PRINT "STOP  FREQ IS:";Stop_freq/1.E+9;"GHz"
1040   PRINT "NUMBER OF POINTS IS:";Npoint
1050   PRINT "SOURCE POWER IS:";INT(Power+.001);"dBm"
1060   PRINT "SWEEP MODE IS:";Swe$
1070   PRINT "ACTIVE CAL SET IS:";Calset
1080   OFF KEY
1090   ON KEY 1 LABEL "Save    State" GOTO Save_state
1100   ON KEY 2 LABEL "Recall  State" GOTO Recall_state
1110   ON KEY 3 LABEL "Change  Freq" GOTO Freq_range
1120   ON KEY 4 LABEL "No of   Point" GOTO No_point
1130   ON KEY 5 LABEL "Power   Level" GOTO Power
1140   ON KEY 6 LABEL "Sweep   Mode" GOTO Sweep_mode
1150   ON KEY 7 LABEL "Calibra-tion" GOTO Call_cal
1160   ON KEY 8 LABEL "Go to   MainMenu" GOTO Main_menu
1170   GOTO 1090
1180 Recall_state:!
1190   INPUT "ENTER RECALL STATE NUMBER:",Sset
1200   OUTPUT @Nwa;"RECA"&VAL$(Sset)
1210   GOTO Setup
1220 Save_state:!
1230   INPUT "ENTER SAVE STATE NUMBER:",Sset
1240   OUTPUT @Nwa;"SAVE"&VAL$(Sset)
1250   GOTO Setup
1260 Freq_range:!
1270   INPUT "ENTER START FREQ IN GHz:",Star_freq
1280   INPUT "ENTER STOP FREQ IN GHz:",Stop_freq
1290   OUTPUT @Nwa;"STAR";Star_freq;"GHz;"
1300   OUTPUT @Nwa;"STOP";Stop_freq;"GHz;"
1310   GOTO Setup
1320 No_point:!
1330   INPUT "ENTER NUMBER OF POINT (51,101,201,401 or 801):"
,Npoint
1340   OUTPUT @Nwa;"POIN",Npoint
1350   GOTO Setup
1360 Power:!
1370   INPUT "ENTER SOURCE POWER LEVEL IN dBm:",Power
1380   OUTPUT @Nwa;"POWE",Power
1390   GOTO Setup
1400 Sweep_mode:!
1410   INPUT "ENTER 1 FOR STEP MODE AND 2 FOR RAMP MODE:",Swe
ep
1420   IF Sweep=2 THEN
1430      GOTO Ramp_mode
1440   ELSE
1450      GOTO Step_mode
```

```
1460  END IF
1470 Step_mode:!
1480  OUTPUT @Nwa;"STEP;"
1490  GOTO Setup
1500 Ramp_mode:!
1510  OUTPUT @Nwa;"RAMP;"
1520  GOTO Setup
1530 Call_cal:!
1540  INPUT "ENTER CAL SET NO (1-8), OR 0 FOR NEW CAL, OR 9
FOR CAL OFF",Cn
1550  IF Cn=0 THEN
1560    CALL Calibrate(Npoint)
1570    GOTO Main1
1580  END IF
1590  IF Cn<9 THEN
1600    OUTPUT @Nwa;"CORRON;"
1610    OUTPUT @Nwa;"CALS"&VAL$(Cn)
1620  ELSE
1630    OUTPUT @Nwa;"CORROFF;"
1640  END IF
1650  GOTO Setup
1660 Default:!
1670  DISP "PRESETTING THE NWA ... PLEASE WAIT."
1680  OUTPUT @Nwa;"PRES;"
1690  OUTPUT @Nwa;"STAR 2 GHz;STOP 18 GHz;"
1700  OUTPUT @Nwa;"POIN801;"
1710  OUTPUT @Nwa;"STEP;"
1720  OUTPUT @Nwa;"CONT;"
1730  OUTPUT @Nwa;"OUTPERRO;"
1740  GOTO Main_menu
1750 !!
1760  STOP
1770  END
1780 !!
1790  SUB Calibrate(Npoint)
1800    OPTION BASE 1
1810    ASSIGN @Nwa TO 716
1820    ASSIGN @Nwa_data2 TO 716;FORMAT OFF
1830    INTEGER Preamble,Size,Cals
1840    DIM Room(801,2),Reference(801,2),Source(801,2)
1850    DISP CHR$(129)&"MEASURE ROOM,"&CHR$(128)&" THEN PRES
S CONTINUE"
1860    BEEP
1870    LOCAL 716
1880    PAUSE
1890    OUTPUT @Nwa;"FORM3;OUTPRAW1"
1900    ENTER @Nwa_data2;Preamble,Size,Room(*)
1910  !
1920    DISP CHR$(129)&"MEASURE REFERENCE,"&CHR$(128)&" THEN
 PRESS CONTINUE"
1930    BEEP
```

```
1940     LOCAL 716
1950     PAUSE
1960     OUTPUT @Nwa;"FORM3;OUTPRAW1"
1970     ENTER @Nwa_data2;Preamble,Size,Reference(*)
1980    !
1990     DISP CHR$(131)&"SUBTRACTING OUT"&CHR$(128)&" THE EFF
ECTS OF THE ROOM"
2000     FOR M=1 TO 2
2010       FCR N=1 TO Npoint
2020         Reference(N,M)=Reference(N,M)-Room(N,M)
2030       NEXT N
2040     NEXT M
2050    !
2060     INPUT "ENTER CAL SET NUMBER (1-8) AND PRESS CONTINUE
",Cals
2070     BEEP
2080     IF Cals=0 THEN GOTO 2060
2090     DISP CHR$(131)&"LOADING"&CHR$(128)&" CAL COOEFFICIEN
TS"
2100     OUTPUT @Nwa;"CAL1;CALIS111"
2110     OUTPUT @Nwa;"FORM3;INPUCALC01"
2120     OUTPUT @Nwa_data2;Preamble,Size,Room(*)
2130     OUTPUT @Nwa;"FORM3;INPUCALC02"
2140     OUTPUT @Nwa_data2;Preamble,Size,Source(*)
2150     OUTPUT @Nwa;"FORM3;INPUCALC03"
2160     OUTPUT @Nwa_data2;Preamble,Size,Reference(*)
2170     OUTPUT @Nwa;"SAVC;CALS"&VAL$(Cals)
2180     DISP
2190     LOCAL 716
2200   SUBEND
2210 !!
2220   SUB Record_data(Npoint)
2230     OPTION BASE 1
2240     ASSIGN @Hpib TO 7
2250     ASSIGN @Nwa TO 716
2260     PRINTER IS 1
2270     REAL Freq(1:801),Mag(1:801),Phase(1:801)
2280     REAL Block(1:801,1:2)
2290     INTEGER Binary(1:801,0:2)
2300     INTEGER I,Points,M,N
2310     COM Exp_tbl(*)
2320     REMOTE @Hpib
2330     ABORT @Hpib
2340     CLEAR @Nwa
2350     Points=Npoint
2360     Enter_data(@Nwa,Points,Binary(*))
2370     Convertb(Points,Binary(*),Block(*))
2380     Transform(Points,Block(*),Mag(*),Phase(*))
2390     CLEAR @Nwa
2400     BEEP
2410     PRINT CHR$(12)
```

```
2420     DISP
2430     GINIT       !*********PLOT GRAPH
2440     GCLEAR
2450     GRAPHICS ON
2460     VIEWPORT 10,140,60,100
2470     FRAME
2480     Maxv=-10000
2490     N=Npoint
2500     FOR I=1 TO N
2510       Maxv=MAX(Maxv,Mag(I))
2520     NEXT I
2530     WINDOW 1,N,Maxv-40,Maxv+5
2540     FOR I=1 TO N
2550       MOVE I,-200
2560       DRAW I,Mag(I)
2570     NEXT I
2580     VIEWPORT 10,140,10,50
2590     FRAME
2600     WINDOW 1,N,-180,180
2610     FOR I=1 TO N
2620       MOVE I,0
2630       DRAW I,Phase(I)
2640     NEXT I
2650 !
2660     PAUSE
2670     GCLEAR
2680 !
2690 !FILE CREATOR
2700     INPUT "ENTER NEW FILE NUMBER =",Istrt
2710     Filen$=""
2720     DISP "WRITING DATA TO DISK.... PLEASE WAIT"
2730     Filen$="F"&VAL$(Istrt)&".DAT"
2740     CREATE BDAT Filen$,26,256
2750     ASSIGN @Path TO Filen$
2760     OUTPUT @Path;Mag(*),Phase(*)
2770     ASSIGN @Path TO *
2780     Filen$="D"&VAL$(Istrt)&".DAT"
2790     CREATE Filen$,256
2800     ASSIGN @Path2 TO Filen$
2810     FOR I=1 TO N
2820       OUTPUT @Path2 USING "K";I,CHR$(44),Mag(I),CHR$(44)
,Phase(I)
2830     NEXT I
2840     GCLEAR
2850     ASSIGN @Path2 TO *
2860   SUBEND
2870 !!
2880   DEF FNAtan(X,Y,P)
2890     IF X=0 THEN X=1.E-9
2900     D=ATN(Y/X)
2910     IF (X<0) AND (Y>0) THEN P=D+PI
```

```
2920    IF (X<0) AND (Y<0) THEN P=D-PI
2930    IF X>0 THEN P=D
2940    RETURN P
2950  FNEND
2960 !!
2970  SUB Print_data(INTEGER N,REAL X(*),REAL Y(*),REAL M(*)
)
2980    INTEGER I
2990    FOR I=1 TO 128
3000      PRINT USING "4(5D.DD)";I,X(I),Y(I),M(I)
3010    NEXT I
3020  SUBEND
3030 !!
3040  SUB Enter_data(@N,INTEGER N,D(*))
3050    INTEGER Preamble,Bytes
3060    OUTPUT @N;"FORM1; OUTPDATA;"
3070    ASSIGN @N;FORMAT OFF
3080    ENTER @N;Preamble;Bytes
3090    N=Bytes/6
3100    REDIM D(1:N,0:2)
3110    ENTER @N;D(*)
3120    ASSIGN @N;FORMAT ON
3130  SUBEND
3140 !!
3150  SUB Transform(INTEGER N,REAL D(*),M(*),P(*))
3160    INTEGER I
3170    REAL R,Im,Mag
3180    DEG
3190    FOR I=1 TO N
3200      R=D(I,1)
3210      Im=D(I,2)
3220      Mag=SQR(R*R+Im*Im)
3230      M(I)=20*LGT(Mag)
3240      P(I)=2*ATN(Im/(R+Mag))
3250    NEXT I
3260  SUBEND
3270 !!
3280  SUB Convertb(INTEGER N,B(*),REAL D(*))
3290    INTEGER I
3300    REAL Exp
3310    COM Exp_tbl(*)
3320    FOR I=1 TO N
3330      Exp=Exp_tbl(BINAND(B(I,2),255))
3340      D(I,1)=B(I,1)*Exp
3350      D(I,2)=B(I,0)*Exp
3360    NEXT I
3370  SUBEND
3380 !!
3390  DEF FNLgt(X,Y)
3400    Z=X^2+Y^2
3410    IF Z>.000001 THEN
```

```
3420        Vlog=10*LGT(Z)
3430      ELSE
3440        Vlog=-200
3450      END IF
3460      RETURN Vlog
3470    FNEND
3480 !!
3490    SUB Playback_data(Npoint)
3500      OPTION BASE 1
3510      ASSIGN @Hpib TO 7
3520      ASSIGN @Nwa TO 716
3530      PRINTER IS 1
3540      REAL Freq(1:801),Mag(1:801),Phase(1:801)
3550      REAL Block(1:801,1:2)
3560      INTEGER Binary(1:801,0:2)
3570      INTEGER I,Points,M,N
3580      COM Exp_tbl(*)
3590      INPUT "ENTER FILE NUMBER =",Num
3600      Fname$="F"&VAL$(Num)
3610      OUTPUT KBD;Clear$;
3620      OUTPUT KBD;Home$;
3630      ASSIGN @Path TO Fname$
3640      ENTER @Path;Mag(*),Phase(*)
3650      PRINT CHR$(12)
3660      DISP
3670      GINIT       !*********PLOT GRAPH
3680      GCLEAR
3690      GRAPHICS ON
3700      VIEWPORT 10,140,60,100
3710      FRAME
3720      Maxv=-10000
3730      N=Npoint
3740      FOR I=1 TO N
3750        Maxv=MAX(Maxv,Mag(I))
3760      NEXT I
3770      WINDOW 1,N,Maxv-40,Maxv+5
3780      FOR I=1 TO N
3790        MOVE I,-200
3800        DRAW I,Mag(I)
3810      NEXT I
3820      VIEWPORT 10,140,10,50
3830      FRAME
3840      WINDOW 1,N,-180,180
3850      FOR I=1 TO N
3860        MOVE I,0
3870        DRAW I,Phase(I)
3880      NEXT I
3890      PAUSE
3900      GCLEAR
3910    SUBEND
```

APPENDIX B. SOURCE CODE OF THE "PROC.M" PROGRAM

```
% Post-processing program
% REV. 6/24/93   Ken Oh

clear,  clg

filename=input('Enter Cal File:    d101 ','s');
eval(['load ',filename,'.dat'])
data1=eval(filename);

filename=input('Enter  BG File:    d102 ','s');
eval(['load ',filename,'.dat'])
data2=eval(filename);

filename=input('Enter Target File: d103 ','s');
eval(['load ',filename,'.dat'])
data3=eval(filename);

filename=input('Enter Computed Sphere Mag File:  mag ','s');
eval(['load ',filename,'.dat'])
data4=eval(filename);

filename=input('Enter Computed Sphere Phase File:faz ','s');
eval(['load ',filename,'.dat'])
data5=eval(filename);

filename=input('Enter Target Mie File: m1, m2, or m3 ','s');
eval(['load ',filename,'.dat'])
data6=eval(filename);

j=sqrt(-1);,   npoint=801;
freq=[2:(18-2)/800:18]';
t=[0:50/800:50]';
t2048=[0:50/2047:50]';
tzoom=[10:10/409:20]';

% ******************************** Calibration Data
m1=zeros(1,npoint);
p1=zeros(1,npoint);
for i=1:npoint
      m1(i)=data1(i,2);               % in db
      p1(i)=data1(i,3);               % in degree
end;
m1=10..^(m1/20);                      % in linear unit
p1=p1*pi/180;                         % in radian
d1=m1.*cos(p1)+j*m1.*sin(p1);
```

```
% ********************************* Background Data
m2=zeros(1,npoint);
p2=zeros(1,npoint);
for i=1:npoint
      m2(i)=data2(i,2);                 % in db
      p2(i)=data2(i,3);                 % in degree
end;
m2=10..^(m2/20);                        % in linear unit
p2=p2*pi/180;                           % in radian
d2=m2.*cos(p2)+j*m2.*sin(p2);

% ********************************* Target Data
m3=zeros(1,npoint);
p3=zeros(1,npoint);
for i=1:npoint
      m3(i)=data3(i,2);                 % in db
      p3(i)=data3(i,3);                 % in degree
end;
m3=10..^(m3/20);                        % in linear unit
p3=p3*pi/180;                           % in radian
d3=m3.*cos(p3)+j*m3.*sin(p3);

% ********************************* Computed Sphere Data
m4=zeros(1,npoint);
p4=zeros(1,npoint);
for i=1:npoint
    m4(i)=data4(i+4);
    p4(i)=data5(i+4);
end;
d4=m4.*cos(p4)+j*m4.*sin(p4);

% ********************************* Target's Mie Solution
m6=zeros(1,npoint);
for i=1:npoint
    m6(i)=data6(i+4);
end;

clg
plot(freq,m3)
title('Target Raw Data')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% *********************************
d12=d1-d2;                        % Subtracting BG from Cal
d32=d3-d2;                        % Subtracting BG from Target

clg
plot(freq,abs(d32))
```

```
title('Frequency Response after Background Subtraction')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% *******************************   Calibration
f32c=d32./d12.*d4;

clg
plot(freq,abs(f32c))
title('Frequency Response after Calibration')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% *******************************   Hamming window
win=hamming(npoint);
f32cw=f32c.*win';

clg
plot(freq,win)
title('Hamming Window')
xlabel('frequency (GHz)'), ylabel('weighting factor')
%printlj
pause
clg
plot(freq,abs(f32cw))
title('Frequency Response after Windowing')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause


% ****************************  Adding zeros and conjugates
ff=zeros(1:2048);
ff([101:901])=f32cw;
ff([1149:1949])=conj(f32cw(801:-1:1));

clg
plot(abs(ff))
title('Frequency Response after Adding zeros and Conjugates'
)
xlabel('index number'), ylabel('magnitude (volts)')
%printlj
pause

tt=ifft(ff);                          % Inverse FFT to time domain
clg
plot(t2048,real(tt))
title('Time Response before Shifting')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
```

```
%printlj
pause

temp=zeros(1:1459);
temp=tt([1:1459]);
tt([1:589])=tt([1460:2048]);
    % Shifting data to put cross-talk at time zero.
tt([590:2048])=temp;
clg
plot(t2048,real(tt))
title('Time Response after Shifting')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause

g1=zeros(1:400);
g2=zeros(1:1248);
tt([1:400])=g1;                    % Gate width = 400 cells
tt([801:2048])=g2;
clg
plot(t2048,real(tt))
title('Time Response after Gating')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause
clg
plot(tzoom,real(tt([411:820])));
title('Zoom-in View of Time Response')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause

ffg=fft(tt);                      % FFT to frequency response
clg
plot(abs(ffg))
title('Frequency Response Showing All 2048 points')
xlabel('index number'), ylabel('magnitude (volts)')
%printlj
pause

f32cg=zeros(1:801);
f32cg=ffg([101:901]);      % throw-away zeros and conjugates
clg
plot(freq,abs(f32cg))
title('Frequency Response from 2 GHz to 18 GHz')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

win_inv=1../win';
f32cg=f32cg.*win_inv;
```

```
clg
plot(freq,win_inv)
title('Inverse of Hamming Window')
xlabel('frequency (GHz)'), ylabel('weighting factor')
%printlj
pause

clg
plot(freq,abs(f32cg))
title('Frequency Response after Unwindowing')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

clg
axis([2 18 -50 -10])
plot(freq,20*log10(abs(f32cg)),'--',freq,20*log10(m6),'-')
title('Frequency Response')
xlabel('frequency (GHz)'),  ylabel('RCS (dBsm)')
grid
%printlj
axis;

end;
```

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